Engineering Geomorphological Assessment and Slope Hazard Identification of the Haast Pass Highway Corridor

State Highway Six, Haast Pass, New Zealand

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Abstract

The Haast Pass highway has had a long history of instability since it was constructed in 1960. Steep slopes and deeply incised river create an actively changing geomorphic environment making maintaining the highway corridor hazardous and difficult. This thesis study provides the first comprehensive investigation of the highway corridor between the Summit and Thunder Creek Falls using LiDAR and detailed air-photo analysis to provide the basis for geomorphic mapping. Management of slope hazards to date has been based on a reactive approach treating the immediate unstable areas around landslides after they occur. This study presents the first large-scale geomorphological assessment of the highway corridor identifying surface unit type, slope processes and slope hazards in order to facilitate the development of a long-term highway management strategy.

Because dense vegetation covers nearly all the slopes above the highway in the study area as as such, it has not been possible to adequately investigate slope geomorphology until the availability of LiDAR. This study is the first to use Light direction and ranging[LiDAR] for corridor hazard mapping beneath dense vegetation in New Zealand. The LiDAR survey was flown by New Zealand Aerial Mapping in January 2014 for the New Zealand Transport Agency and was provided for use in this study. The LiDAR surface model created serves as the basis for mapping surface units and landslide features, enabling the identification of slope processes and landslide hazards. Aerial photos were also used to identify surface unit type and slope processes where vegetation was absent and enabled the activity of slopes to be evaluated. Interpretations made using LiDAR were validated using aerial photography and targeted ground truthing with all ground truthing sites confirming the interpretations made.

Large scale geomorphology mapping was undertaken on slopes above the highway on the western side of the valley and showed that there were distinct differences between the southern and northern parts of the highway corridor. Between The Haast Pass Summit and Pipson Creek the slopes are dominated by schist bedrock with regolith confined to small deposits next to the highway and larger deposits in tributary valleys. The slope hazards affecting the highway in this zone are confined to debris sliding and rockfall from regolith deposits and bedrock cliffs next to the highway between Robinson and Pipson Creeks. The slopes between Pipson Creek and the Gates of Haast, in contrast, consist of deep regolith deposits and regolith veneered slopes. Evidence of active and recently active slope processes on the slopes facing the highway confirm the instability is associated with slope hazards including debris flows, debris slides, rockfall and highway collapse.

Small-scale detailed evaluations were undertaken at Diana Falls, Ford Creek, The Hinge and the Gates of Haast with the sites selected based on their history of instability and/or their particularly hazardous appearance during the large-scale geomorphology and hazard identification. Using the LiDAR surface model surface units and landslide features were identified and mapped with small-scale engineering geomorphology maps. This information was then used to interpret the subsurface geometry and the failure mode/slope processes acting on the slope enabling an assessment of the current stability and future slope development to be made. Diana Falls was found to have scarps and tension cracks running across the regolith covered slope indicating that future landslides from this site will be an on going problem. At Ford Creek the landslide was identified as a rock compound slide, but assessments of its current stability and future development were unable to be made. Detailed investigations at The Hinge revealed evidence of a large creeping debris slide and the existence smaller debris slides below the highway through the entire investigation area; the debris slides identified show signs of activity and continued debris sliding will continue to affect the highway in the future. The investigation of the Gates of Haast revealed that the slope instability is not as extensive as it has been in the past, however, recent rock slides and debris flows have continued affect the highway and will continue to pose a hazard in the future.

This thesis provides fundamental information required to develop a comprehensive management plan for the Haast Pass highway corridor between the Haast Pass summit and the Gates of Haast. A new landslide management plan has been developed outlining immediate, short-term and long-term options and programmes that should be implemented. Immediate options are steps that can be taken to quickly increase the safety of road users and include moving of highway closure gates and installation of warning signage. Short-term options aim to mitigate landslide hazards where feasible including the installation of rockfall barriers and debris flow attenuators, and lay the groundwork for future avoidance of hazards by undertaking investigations of highway realignment and developing highway closure rainfall thresholds. Long-term options are recommended where landslides will continue to impact the same section of the highway repeatedly and focus on hazard avoidance by building landslide shelters or major highway realignments. The adoption of a management plan ensures security of the highway, protects against loss of life and provides the most cost effective long-term solution to manage the landsliding hazards.

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Chapter 1

Introduction

1.1 Context and Background

The highway (SH6) links Makarora, at the head of Lake Wanaka, with the West Coast of the South Island near Jacksons Bay. A pack-track connected Haast with Makarora from 1879, providing connection between the West Coast and the Central Otago goldfields. However, road connection was not established until 1960 between Makarora and Haast, and the final link to the highway network was the Haast-Paringa section completed in 1965 (Gilkison and Galloway 1971, Pope and Pope 1986).

The Haast Pass is the lowest of the alpine passes through the Southern Alps, but highway completion was vital to connect the West Coast and Central Otago via the only feasible southern route. Initially road building began by linking Hawea with Makarora at the top of Lake Wanaka in 1931. Over the next nine years work on the West Coast side pushed the road as far as the Gates of Haast at the entrance to the pass. Work on the road ceased during World War 2 with a shortage of funds and workers, thus resulting in no progress being made until work began again in 1956. Four years later in 1960 the road through the Pass was completed linking Haast with Wanaka (Pope and Pope 1986, Grantham 2010). Substantial engineering challenges were addressed using the technology of the time, particularly in building on steep slopes that requiring extensive blasting of the schist bedrock to form cuts. Highway and remained a gravel track until it was finally widened and sealed in 1995 (Malcolm 2007, Grantham 2010).

Today the highway is travelled by 600 vehicles per day made up of a mix of cars, camper vans and buses, most of which driven or occupied by tourists following the tourist circuit down the West Coast and continuing on the Otago and Fiordland (Opus 2013b). For 80km the highway between Haast and Makarora is completely devoid of any settlements, and until recently cell phone reception was absent from most of the route and the pass itself. The importance of this link cannot be understated with the detour required to reach Wanaka from Haast if the road is closed adding an additional 740km to an otherwise 140km journey. Closures of the highway can also have adverse effects on the West Coast economy with tourists choosing not to travel to the tourist centres of Hokitika, Haast and the glaciers at Franz Joseph and Fox, because of the 300km of back tracking required across Arthur's Pass.

On the night of the 10th of September a series of landslides impacted the highway within the Haast Pass. A debris flow originating from Pipson Creek is thought to have been responsible for the deaths of two tourists that were struck and washed down slope into the Haast River and killed(Logie 2015); the debris flow also resulted 30m of highway being inundated and requiring significant clearing works (E. Stevens (Opus), personal communication, April 21, 2014). The largest in the series of landslides occurred at Diana Falls where 30,000m^3 of debris inundated the highway, closing it for several days and resulting in an ongoing landslide hazard from residual debris falling and impacting the highway (Opus 2013b). These events question the level of detailed knowledge of geotechnical hazards potentially impacting the Haast Pass highway, and resulted in a LiDAR survey being flown that has highlighted the extend of instability affecting the forested slopes above the highway. This thesis presents the first geomorphological assessment of the Haast Pass highway corridor, and has used new technology that has not previously been trialled in New Zealand for this purpose.

1.2 Scope of Project and Objectives

The aims of this thesis are to map the hillslope geomorphology and identify the landslide hazards on slopes above the Haast Pass highway that are obscured by vegetation, to evaluate the impact that the hazards will have on the highway corridor and propose methods for avoiding and/or mitigating the hazards. LiDAR technology will was to image the slopes above the highway corridor. This is the first time that this technique has been used in New Zealand for highway corridor geomorphology and hazard identification. The specific objectives of the thesis are provided below;

1. To evaluate if a combination of LiDAR, aerial photo analysis and targeted ground truthing can be used to reliably identify surface units, landslides and slope processes beneath dense vegetation in the Haast Pass.
2. Undertake large scale engineering geomorphology mapping of surface units, slope processes and landslide features within the Haast Pass primarily using LiDAR. The aim of mapping the hillslope geomorphology is to identify potential slope hazards and prioritise a number of selected hazardous slopes for more detailed engineering geomorphology investigations.
3. Undertake small scale engineering geomorphological investigations at four selected hazardous sites based on the findings of the large-scale LiDAR analysis to identify surface units, landslide features, subsurface geometry, failure mechanisms, current slope stability and future slope development.
4. Use the large-scale and small-scale engineering geomorphology investigations to identify hazards the highway is exposed to and propose methods of avoidance, mitigation and corridor wide management that can be implemented to reduce the impacts that the hazards have on the highway and its road users.

1.3 Study Area

The Haast Pass is located in the southwest of the South Island and links southern Westland with North Otago. The Pass forms the southern most crossing of the Southern Alps with Arthur's Pass 200km to the north and Lewis Pass 300km north. The study area itself covers the slopes above the highway between the Haast Pass summit and Thunder Creek Falls car park near the Burke River confluence with the Haast River. In total 14km of highway and 16m^2 of slopes above are located within the field area with the full extent of the slopes investigated in this study indicated in Figure 1.1C.

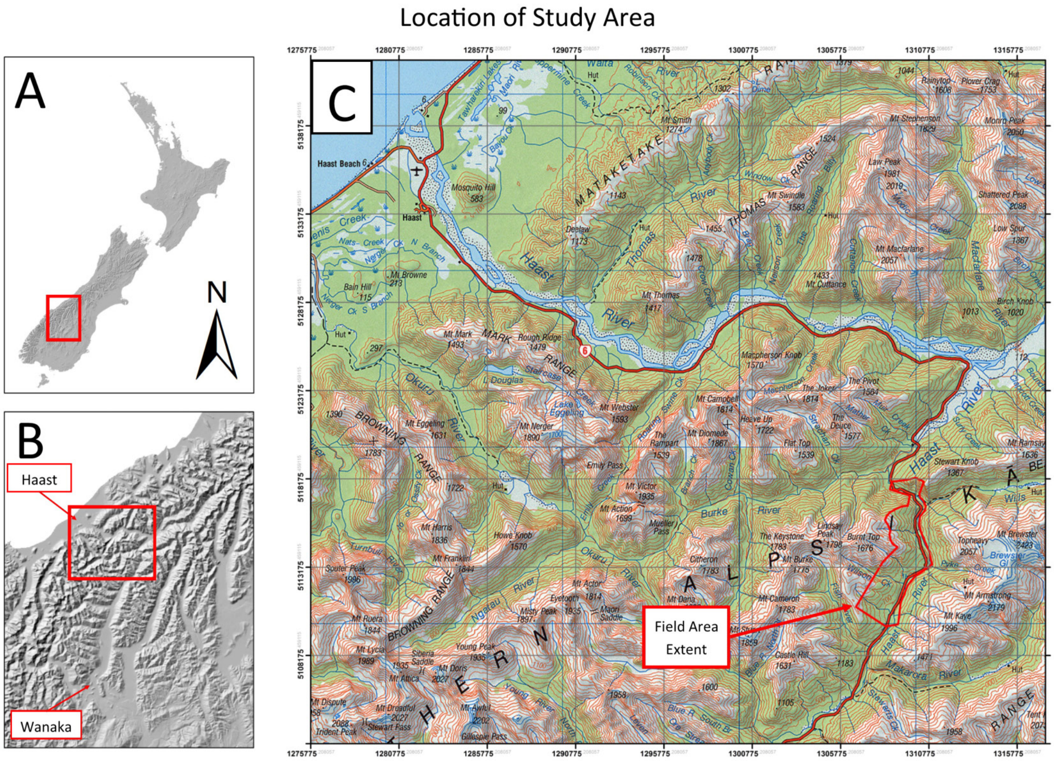

Figure 1.1: Location of the thesis study area. A) New Zealand 25m hillshade image with the location of B shown by the red area. B) Hillshade image of South Westland and North Otago with the location of the topo map in C shown by the red rectangle. C) Topo 250 (21). The location of the project study area is indicated by the red outlined area at the bottom right of the image with SH6 indicated by the dark red line. The Haast township is in the top left corner with the Southern Alps running across the bottom of the map.

The topography of the field area is highly variable with the highway situated at the bottom of a deep valley following the true left side of the Haast River through most of the field area. The highway is surrounded by the peaks of Mt Brewster(2516m), Mt Armstrong(2174m) and Mt Kaye(1998m) on the eastern side of the valley with Powder Flask Peak(1690m) and Burnt Top(1679m) on the western side above the highway. From the Haast Pass summit at 562m the highway descends to 450m following the Haast River in a 50m to 100m wide floodplain until Pipson Creek, approximately half way through the field area, where the Haast River enters a gorge. From the top of the gorge at Pipson Creek the highway descends from 450m to 150m at the Thunder Creek Falls car park, at the northern extent of the field area, with the highway situated between 50m and 100m above the river. Steep slopes rise above the highway with slope angles ranging from 20 to 40 degrees with localised slopes between 40^o and 60^o.

The Haast Pass is situated in a transition zone between the wet west coast climate and the dryer eastern regions. Rainfall at Haast township is approximately 3400mm per annum, rising to 4500mm at the Haast Pass summit before dropping to 2500mm at Makarora township (Department of Conservation[DoC] 2006). This dramatic change in precipitation combined with the moderate topographic change through the Haast Pass result in different vegetation types in the northern and southern extents of the field area. Mountain beech forests with sparse understories consisting of twiggy trees, shrubs and carpet mosses characterise the south of the field area while more diverse silver beech forests consisting of kamahi, rata and tree ferns form a very dense canopy and understory in the north (Gilkison and Galloway 1971, DoC 2006).

1.4 Regional Geology

1.4.1 Plate Boundary Setting

New Zealand is positioned in a highly active geologic location where the collision of the Pacific and Australian plates are taking place resulting in significant deformation of the earths crust (Fig 1.2). Through the South Island of New Zealand the plates move in an oblique strike-slip regime where the Pacific Plate moves southwestward and is uplifted in approximately a 10:1 ratio. It is the vertical uplift that has caused the exhumation of deep crustal rocks that now form the mountain range known as the Southern Alps that run the length of the South Island from Nelson through to Fiordland (Mortimer 2004). Most of the rocks exposed along the Southern Alps originated as as sediment acreeting on the margins of Gondwana that are known as terranes and are distinguished based on process of formation and origin of the material.

The rocks of the South Island of New Zealand are made up of terranes composed predominantly of siliciclastic sandstones and mudstones referred to as graywacke-argillite rocks some of which have been metamorphosed. Plutonic rocks can be found in the southwest and northwest of the South Island occurring in a number of batholiths consisting of gabbroids and granitic rocks that have been overprinted by metamorphic events in places. Sedimentary rocks of Paleogene and Neogene in age can be found east of the Alpine Fault and once covered the terranes of the South Island before uplift of New Zealand promoted erosion and removal (Rattenbury et al. 2010).

1.4.2 Regional Geology

The basement rocks of the Haast, Makaroa and Lansborough Valleys are known as the Haast Schist Group and are associated with the metamorphosed fringes of the Rakaia Terrane and Calpes Terrane. The Haast Schist rocks extend in a 100km belt across Otago and northeastwards from Haast in a narrow 20km band east of the Alpine Fault as shown in Figure 1.2 (Mortimer 2004). Hasst Schist Group rocks in Otago are known as the Otago Schist while the Schist along the Alpine Fault are referred to as Alpine Schist. The Otago Schist consists of metamorphosed fringes of both the Caples and Rakaia terranes where as the Alpine Schist is only the metamorphosed portions of the Rakaia Terrane.

The Otago and Alpine Schist differ in their degree of metamorphism and age of uplift. Otago Schist is of low metamorphic grade and is dominated by psammitic and pelitic grayschist with some greenschist and quartzite(Mortimer 2004). The Otago Schist was metamorphosed during terrane collision in the late Mesozoic and resulted in the mountain building episode known as the Rangitata Orogeny that exposed the schist at the surface approximately 110Ma (Mortimer 2004,

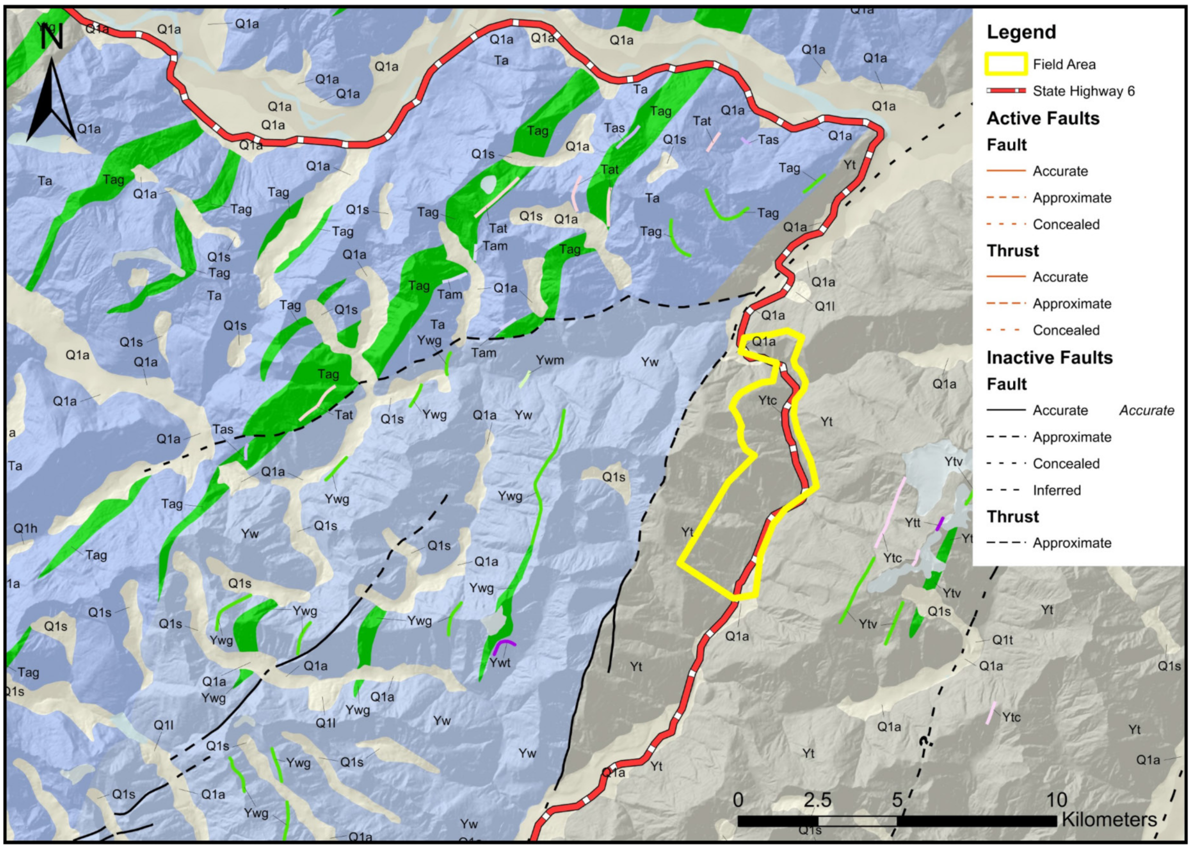

Figure 1.2: Map showing the regional geology of the Haast area with state highway six and the extent of the project field area indicated (Map modified from the QMap provided with Rattenbury et al. (2010)). **Yt** = Pelitic semi-schist and Grayschist. **Yw** = semischist. **Ywg** = Greenschist. **Ta** = Pelitic ans subordinate psammitic schsit. **Tag** = Greenschist and amphibolite. **Q1a** = Quaternary alluvial and fan deposits. **Q1s** = Quaternary scree and colluvial deposits. Relevant sections from the Haast Geological Map key are included in Appendix A, but use the geological unit text annotations to identify units as the colours are not exactly the same.

Adams and Gabites 1985). The Alpine Schist is dominated by K-feldspar, oligoclase and garnet zones reflecting its higher metamorphic grade compared with the Otago Schist. Alpine Schist is much younger in age compared to the Otago Schist with the oldest rocks exposed at the surface 20 million years ago and is still being actively uplifted today along the Alpine Fault (Mortimer 2004, Adams and Gabites 1985).

The Study area is focused in the Haast River Valley in a transition area between the Alpine and Otago Schists. The age of the schist as well as changes in textural zonation represent the change from Haast to Alpine Schist. Younger rocks towards the coast in the study area display potassium-argon ages of approximately 20ma while towards the southeastern portion of the study area the ages are between 90-120ma Adams and Gabites (1985). The schist also undergoes a change from low-grade chlorite zone greenschist facies near Lake Hawea to medium-grade biotite and garnet greenschist facies in the Haast Valley to a high-grade amphibolite facies near the Alpine Fault (Rattenbury et al. 2010).

1.4.3 Regional Structure

The Major structural feature in the Haast area is Alpine Fault that marks the boundary between the Pacific and Australian plates. The Alpine Fault accommodates 70-75% of the total plate movement of 39-48 mm/yr with movement occurring as strike slip movement with a small component of uplift approximately 10% of the strike slip movement. Nearly all the movement is taking place on the Pacific Plate and as a result deformation is more pronounced and more easily identified (Wallace et al. 2007).

The uplift of the deep crustal rocks along the Alpine Fault has resulted in extensive deformation that results in numerous faults and folds throughout the region Figure 1.1. The major faults running through the study area are aligned approximately parallel with the trace of the Alpine Fault and are the Castle Hill and Burke Faults with the former occupying the Haast river valley north of Makarora (Rattenbury et al. 2010). Uplift and deformation has also lead to the reorientation of the schist with the dip directions rarely flat.

Dip direction of the schist is consistently east southeast in the Haast River Valley with folds found closer to the Alpine fault and further east towards the Hunter Valley. The Schist in the Haast river valley dip eastwards with dips ranging from 30^{o} to 80^{o} and strike approximately parallel to the river alignment in a generally north easterly trend (Rattenbury et al. 2010). The dip and dip direction combined with steep topography results in topple and sliding failures on the western side of the Haast Valley and wedge or circular failures on the eastern side of the valley.

1.5 The Engineering Geomorphology Approach to Corridor Investigations

1.5.1 Principles

The engineering geomorphology approach combines both a strict engineering geology approach and a geomorphological approach to get a more complete understanding the landscape. Traditionally corridor investigations have been undertaken using an engineering geology approach to investigation, as it has become accepted as a critical component of the geotechnical investigations (Fookes 1997). The main problem with a strict engineering geology approach, is that often there is not sufficient data with which to assess geomorphological hazards. In engineering geology investigations, the tendency is to focus on lithology, structure and substrate data alone as a snapshot in time (Hearn 2002). In contrast, the geomorphological approach is concerned with the understanding of landforms, processes and landscape evolutionary changes over longer time-scales. The ability to read the landscape and predict the magnitude, frequency and location of geomorphological events is a key strength of the geomorphological approach (Dearman and Fookes 1974, Jones 1983). Combining the interpretation of geomorphological processes and hazards with the ability to read the landscape with regard to landscape evolution over time is where the field of applied geomorphology has the most to contribute to corridor investigations.

The engineering geomorphology approach combines the applied geomorphology understanding of the landscape with a working knowledge of the engineering geology and engineering design. The outcome is an approach that provides a better understanding of the landscape interaction and hazards that a particular corridor alignment is exposed to than an engineering geology approach alone does (Hearn 2002). The primary benefit is that geomorphological hazards can be recognised, avoided or minimised, thus providing a great benefit to engineering project design or rehabilitation (Griffiths and Hearn 1990). The effectiveness of the engineering geomorphology approach to corridor investigation, improvement and rehabilitation is best illustrated by its use in practice as discussed in the case studies below.

1.5.2 Case Studies

The effectiveness of the engineering geomorphology approach to mountain highway corridor design and investigation has been illustrated in Nepal by Brunsden et al. (1975a,b,c). The Dharan-Dhankuta road was constructed between 1974 and 1982, through some of the most difficult terrain in Nepal providing one of the few alignments between the lowland plains and the mountainous hinterlands. The initial feasibility study recommended an alignment that crossed through considerably unstable terrain. The engineer in charge of construction was unconvinced and instead commissioned an engineering geology consultant to undertake an investigation of the proposed corridor alignment and investigate possible alternatives. Subsequently an engineering geomorphology investigation was undertaken that identified the proposed alignment as unsatisfactory and undertook further engineering geomorphology mapping to identify alternatives (Brunsden et al. 1975a,b,c). The recommendation of the engineering geomorphology investigations and mapping program was that a new alignment was identified based on road design requirements and an understanding of the interaction between the landscape and highway as well as changes to this through time. It enabled the identification of hazardous slopes and made it possible to recommend corridor alignment changes to avoid these areas.

Detailed reviews of the recommendations made during the Dharan-Dhankuta road project were undertaken in 1984 and again in 2000, focusing on the effectiveness of sections where engineering geomorphological recommendations were implemented and areas where they were not. The 1975 surveys identified numerous slope failures on or close to the proposed road alignment and recommendations were made to realign the highway to the upper slopes in half of theses cases. Two thirds of the locations reccomended for realignment were implemented with the remaining third that were not having suffered considerable and continuing instability in 1984 and having costed up to five times the price of the proposed realignments (Hearn 1987). A particularly heavy rainstorm in 1984 resulted in extensive landsliding in the corridor valley with 95% of all landslides occurring on the lower slopes; the decision to move the highway to the upper slopes based on the engineering geomorphology investigation was vindicated by its ability to recognise and avoid these hazardous zones (Hearn 1987). A review of the highway in 2000 found that the corridor alignment based on sound engineering geomorphology enabled the highway to avoid the most hazardous areas, resulting in its continued resilience after significant floods in 1984, 1987 and in 1988 as well as an earthquake in 1988 Hearn (2002).

The engineering geomorphology approach to hazard avoidance and corridor alignment selection has been implemented more recently in Tanzania during the construction of an access road for a hydro project. The study, undertaken by Marwa and Kimaro (2005), informed the Tanzania Electric Supply Company[TANESCO] of the optimal alignment to avoid slope hazards and minimise effects on the environment over the 17km length of the access road. Engineering geomorphology mapping was undertaken with the aim of identifying steep unstable slopes, deep gulleys and landslides. This enabled the highway to be aligned to either avoid the hazard or where not possible, design appropriate engineered structures or modified highway design to avoid reactivating landslides and reducing the impacts of other hazards. The study concludes that while extra expense was required for the investigation realignment and hazard reduction measures, it was the only solution to secure route security and reduce long-term maintenance costs.

Both of the case studies provided previously deal with construction of new roads where alignment can be adjusted, however, this method has also been used as a way of identifying the hazards in existing corridors as part of qualitative risk assessments. A study by Ellis et al. (2011) used engineering geomorphology as the basis for identification of landslides over a 38km stretch of the M25 motorway corridor after several shallow landslides resulted in damage to the motorway pavement, services, earthworks and structures. Due to the large size of the study area field mapping was not considered feasible and instead a combination of good quality stereoscopic aerial photos and high resolution LiDAR were used to identify the subtle indicators of landsliding. The study identified 13 landslides that were confirmed by ground truthing mapping exercises. This new information allowed the qualitative determination of the risk of landslide events and demonstrates the effectiveness using LiDAR in areas of poor exposure and the importance of ground truthing. It highlights the effectiveness of using the engineering geomorphology approach to corridors that have all ready been constructed as a way of identifying and assessing the landslide hazards.

The ability of this methodology to identify the landslide hazards in existing corridors is particularly helpful in this study as the highway alignment has already been constructed with limited ability for realignment. While it has not been feasible to undertake an engineering geomorphology mapping and investigation of this scale and detail in the Haast Pass previously, due to dense vegetation obscuring most of the ground surface. The combination of the engineering geomorphology approach with the advent of new high resolution LiDAR scanning provides the tool with which to evaluate the hazards the highway faces today and will face in the foreseeable future. While the ideal solution to minimise the cost of ongoing maintenance and ensuring route security would be to undertake an engineering geomorphology study at the time of alignment construction, it can still provide invaluable information of the hazards that the existing alignment is exposed to and enables appropriate management techniques to be implemented.

1.6 Previous Investigations in the Haast Pass Highway Corridor

Previous investigations in the Haast Pass are limited to several detailed engineering reports investigating very small areas of the pass. The approach to initiate an investigation has been either a reaction to a very large landslide; a series of landslide events, or as part of and investigation for highway bridges across the river at the Gates of Haast. This approach to engineering investigations has lead to only three relatively small areas being investigated in detail, two as a response to landslide events and the other as a combination of investigation for the original bridge and a deep seated landslide investigation close to the bridge abutment. The three areas investigated in detail include the areas around Diana Falls, The Hinge and the Gates of Haast; all of which have been the subject of landslide investigations, with the Gates of Haast area also being the subject of investigations related to bridge construction and river scour protections. Details of the investigations and findings of the engineering reports for each site are summarised below.

The most recent landslide investigation in the Haast Pass is centred around Diana Falls where a very large debris slide occurred on the 10th September 2013. The investigations consisted of a detailed initial geotechnical appraisal followed by a LiDAR survey focused on the area around the current failure (Opus 2013b, 2014). The geotechnical investigation (Opus 2013b) found that between 2m and 5m of landslide derived debris covered large rock masses that were inferred to be bedrock based on measurements of foliation defects within the rockmass. The report also noted that part of the headscarp contained a large rockmass of schist with defects forming large blocks that were toppling out and falling down slope. One of the more interesting features was the identification of numerous tension cracks within the landslide debris on either side of the recent failure suggesting that the areas around the current slip may also be susceptible to failure. The LiDAR survey and associated report (Opus 2014) for Diana Falls focused on understanding the geomorphology of the immediate area surrounding the current failure; there was a particular emphasis on identification of structural features of the schist rockmass as well as identifying tension cracks on the slope on the south side and above of the current failure. While both reports provided highly detailed information on the Diana Falls area they still leave large areas of the pass un-investigated. Fortunately, the New Zealand Transport Agency was convinced to collect LiDAR data for the entire pass as well as Diana Falls as a considerable portion of the cost of the survey was in mobilisation of the equipment. It is this LiDAR data of the entire pass that was used in this thesis to investigate the slopes above the highway (The full extent of the LiDAR survey is shown in Appendix C).

The area around The hinge was investigated following displacement of the highway as a result of a debris sliding. The investigation (Opus 2001) followed the road dropping 650mm over a distance of 120m after a period of particularly heavy rainfall in the preceding three days. After the initial failure the road surface continued to creep at a rate of approximately 2.5mm per week. The investigation involved detailed mapping of the slope above and below the highway over the 120m distance. The mapping found evidence of fresh scarps within regolith material above the highway that consisted of large boulders in a silty/sandy matrix. Material below the highway was of similar composition with evidence of a fresh lateral scarp traceable on the southern extent of the landslide. The investigation concluded that the best course of action was to allow the slope to continue to slip and repair the road seal as it became damage. Personal communications with Opus personnel in 2014 indicated that the area is still slowly creeping with seal repairs having been completed recently. This area is investigated in detail in Chapter 5 of the thesis where new insights from LiDAR imagery provide more details on the extent of the larger slope failures around The Hinge.

The area around the Gates of Haast in the vicinity of the highway bridge has had a long history of instability and engineering investigations. Early investigations focused on investigation of the areas around the bridge piers during construction as well as when concerns were raised for the stability of the approaches. These investigations concluded that the southern abutment was founded in schist bedrock that could potentially be susceptible to block slide failures while the northern abutment and approaches were formed across large areas of landslide debris that were causing problems with active debris slides and debris flows impacting on retaining structures as well as rockfall from the slope above the bridge abutment (Paterson 1961, 1979, 1980, 1994). Material below the highway was also showing signs of distress with scour of the landslide debris below the highway causing problems for the highway below the bridge as well as threatening the stability of the northern bridge abutment (Ministry of Works[MoW] 1987). More detailed subsurface investigations involving drilling were conducted in the 2000's initially to investigate the landslide just downstream of the bridge and subsequently as part of an investigation for a new bridge pier (Opus 2002, 2006). The reports found that thickness of landslide debris were up to 50m thick at the centre of the landslide with bedrock ridges dipping steeply on the margins.

Although previous work has been highly detailed it only provides insights into a small number of areas leaving vast regions of the pass un-studied and hazards un-recognised. The LiDAR data that was flown after the 2013 Diana Falls failure is used in this thesis to provide a more complete picture of the nature of the slope above the highway and to provide context to the studies done previously. In this thesis the information from previous studies above is combined with the new high resolution LiDAR data to re-evaluate the areas in greater detail and provide a wider context to the previous investigation findings.

1.7 LiDAR Overview

1.7.1 Basic Principles

Light direction and ranging (LiDAR) is a relatively new tool that provides highly detailed topographic information of the surface of the earth. The method works on the principal of measuring the round trip travel time of an infra red laser pulse from a known point in space to the surface in question and back to a receiver (Wehr and Lohr 1999, Petrie and Toth 2008). The laser pulse leave a transmitter and travels through the atmosphere to the ground where it is reflected by tree branches, bushes and hopefully the ground surface. In most cases the pulse hitting a tree branch or bushes does not result in all the lasers energy being reflected with most of it carrying on through to the ground. The result of this partial reflection is that the energy observed by the receiver is not an instantaneous pulse but rather a waveform signal as shown in the example in Figure 1.3 (Petrie and Toth 2008). While full waveform analysis is beginning to become used the technology required was not used in this survey; Instead the sensor picked four points on the waveform that are then processes and filtered. With careful processing of this returned signal the returns from obstacles can be filtered to only leave the ground surface returns.

1.7.2 LiDAR Data Acquisition

The most common method used to collect LiDAR data for landslide and geomorphology studies is laser scanning (Höfle and Rutzinger 2011). Laser scanning consists of a laser transmitter and a scanning mechanism, typically utilising a rotating mirror or prism, that directs laser pulses over an area rather than just along a profile as seen in Figure 1.4 (Petrie and Toth 2008). Laser scanning systems are typically mounted on aircraft that fly a series of flight lines over an area in question

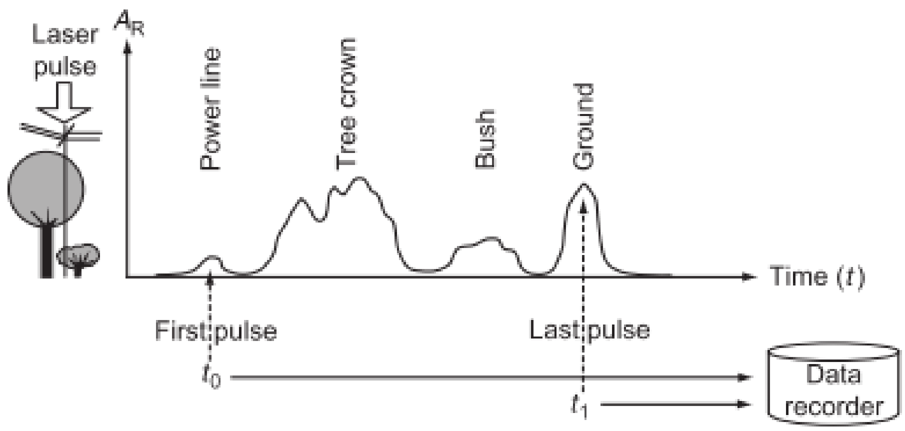

Figure 1.3: An example of the returned waveform of a laser pulse that has passed through obstacles on the way to the ground. Energy intensity (AR) measured from the reflected laser pulse through time (t) is shown on the graph with each obstacle reflecting some of the pulses energy. Many laser scanner will analyse the waveform and pick the peaks in intensity to represent returns (Petrie and Toth 2008).

and can cover large areas relatively quickly (Höfle and Rutzinger 2011, Petrie and Toth 2008). Since the aircraft is moving while the scan is taking place a global navigation system and an inertial measurement unit are required to accurately track the aircrafts location in space to ensure the accuracy of the data (Höfle and Rutzinger 2011). During the LiDAR survey a number of ground control points are also take to compare the elevations of the LiDAR data so as to eliminate any systematic errors that may have occurred during the data acquisition (Kraus and Pfeifer 1998).

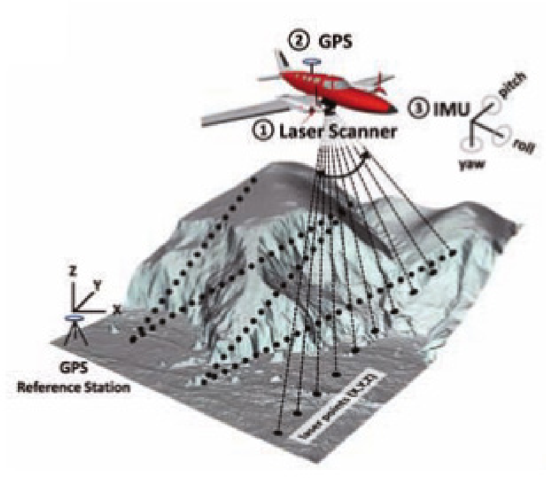

Figure 1.4: The setup for a LiDAR survey using airborne methods of data collection is shown above. The aircraft flys over the surface in question sending out laser pulses in an arc beneath the aircraft. This results in a swath of data points across an area below the aircraft shown by the black dots on the ground surface. In order to know the location of these points on the ground the location of the aircraft is measured using ground based and airborne GPS stations and the movement of the aircraft is tracked using an internal measuring instrument/unit (Höfle and Rutzinger 2011).

1.7.3 LiDAR Survey Output and Processing

The product of LiDAR scanning survey consists of files containing millions of points with X, Y and Z coordinates in 3D space. The points include all reflections detected by the laser scanner receiver and will include tree canopy, bushes and other non-ground reflections (Petrie and Toth 2008). In order to use the data for the generation of a ground terrain model the data must be processed to remove all non-ground reflections. This is achieved by using computer software to filter out the vegetation returns using a number of different approaches and algorithms outlined in (Pfeifer and Mandlburger 2008, Höfle and Rutzinger 2011). The filtered data is then checked using aerial photography to verify that the processed LiDAR data is free from errors, such as the removal of narrow gullies such as gorges and that vegetation has been removed from all areas. The process of filtering the raw LiDAR data to remove vegetation can result in up to 80% of the total number of points being lost. The product of this processing is known as a ground point cloud with the remaining X,Y and Z points representing the LiDAR shots that reached the ground surface. It is the ground point cloud that is then interpolated to form a continuous surface known as a digital terrain model[DTM].

1.7.4 Ground Point Cloud Interpolation and DTM Generation

In order for the ground point cloud to be visualised as a continuous surface representing the ground surface beneath vegetation it must be interpolated. Interpolation is the process of reconstructing the surface of the Earth using a discrete set of elevation data points (El Sheimy et al. 2005). There are a number of statistical methods of fitting a surface between the ground points with the most common techniques including Kriging, nearest neighbor[NN] and inverse distance weighting[IDW]. Kriging interpolation is the best approximation for interpolation of a surface, but is not necessarily the most appropriate for LiDAR data; the large number of data points and the high point densities of LiDAR surveys make kriging interpolation computationally intensive to undertake without significant improvements over less complex methods (Pfeifer and Mandlburger 2008, Guo et al. 2010). Instead NN or IDW interpolation methods are commonly used as they are less computationally intensive and give a satisfactory interpretation of the surface when a dense data point cloud is used relative to the visualisation resolution (Guo et al. 2010). The output of the interpolation is a continuous raster surface with the surface divided up into gridded cells each with an elevation value. This raster surface can then be visualised as a hillshade, slopeshade or surface aspect image in a GIS environment. With appropriate software a 3D visualisation can be used to view the surface.

1.8 LiDAR Applications and Use in Past Studies

LiDAR technology has been utilised by many different disciplines interested in the high resolution topographic information that it can provide. It has been widely implemented in forestry industry and research for its ability to rapidly generate extensive forestry inventories with detailed three dimensional data on forest structure and predictions of biomass within forested areas (Wulder et al. 2008, Akay et al. 2009, Estornell et al. 2011). It has been used by tectonic studies where its ability to generate very high resolution models of the Earth's surface have enabled detailed mapping of fault offsets, structure and surface deformations providing new insights into tectonic forcing of landscapes (Meigs 2013). LiDAR has also been widely used in geomorphology studies where its ability to provide highly detailed topographic models of the Earth's surface provide highly detailed base maps, enable the recognition of large scale morphological trends and enabled detailed quantitative analysis of the temporal and spatial changes of environments (Höfle and Rutzinger 2011, Roering et al. 2013). Landslide investigations have also begun to use LiDAR as a tool for detection and characterisation of landslides for the development of hazard maps, modelling and monitoring with both airborne and terrestrial laser scanning systems being used (Jaboyedoff et al. 2012).

The ability of LiDAR surveys to resolve subtle changes in topographic surface has enabled identification of features in the landscape that have not been previously recognised. This ability to resolve subtle features has been used in tectonic studies to identify fault scarps and surface deformations easily visible in LiDAR surfaces as persistent linear features, but are not easily identifiable due random topographic variations in ground investigations and not resolvable in aerial photography or satellite imagery due to their small surface expressions or anthropogenic modifications of the landscape (Kondo et al. 2008, Székely et al. 2009, Lin et al. 2013b, Migo et al. 2013, Sutinen et al. 2014b). In geomorphology studies its ability to identify subtle structures has been used to resolve bedrock structure in areas of poor exposure as well as enabling the identification of glacial fabrics not otherwise visible (Pavlis and Bruhn 2010, Dyess and Hansen 2014), and have also enabled the identification of subtle features in landscapes that have gone unrecognised by previous studies (Webster et al. 2006, Dowling et al. 2013).

LiDAR technology has also enabled highly detailed imaging of the ground surface in areas of dense vegetation where other methods of DEM generation have been unable to see. This ability has enabled mapping of new faults and fault structures with low relief in regions covered by dense vegetation (Cunningham et al. 2006, Székely et al. 2009, Sutinen et al. 2014b). A number of examples on the west coast of New Zealand, focused on studying the Alpine Fault, have proved the ability of LiDAR surveys not only to penetrate very dense vegetation typical of the west coast, but also still provide high enough resolution LiDAR data with which to make detailed tectonic interpretations (Barth et al. 2012, De Pascale et al. 2014, Langridge et al. 2014).

LiDARs ability to penetrate vegetation has also revolutionised the way in which landslide inventories and studies are conducted with the ability to detect subtle landslide features combined with accurate location information for ground investigation increasing the speed and accuracy of such studies (Eeckhaut et al. 2007, Kasai et al. 2009, Ellis et al. 2011, Lin et al. 2013a, Konsoer and Kite 2014, Sutinen et al. 2014a). Since the advent of LiDAR used for mapping of landslides research has moved towards automated recognition primarily using surface roughness as an indicator of landslide/slope processes activity and age (McKean and Roering 2004, Grohmann 2011, Berti et al. 2013). While this approach was considered for this study, the relatively small area being investigated combined with initial observations of the LiDAR surface from the Haast Pass that indicated the overall appearance of the surface was very rough in most areas making differentiating areas of landsliding from those that are not would be questionable. Artificial roughening of surfaces as a result of very dense vegetation cover was observed in initial LiDAR surface observations where a decrease in ground point resolution and an increase in roughness was not necessary reflective of the ground surface.

1.9 Thesis Layout

- **Chapter 2** provides an overview of the key terminology used throughout the thesis, information on the LiDAR survey and data processing, and an overview of the methodology used in the geomorphology mapping and hazard identification in the Haast Pass.

- **Chapter 3 and 4** cover the geomorphology and hazard identification in the Haast Pass, with analysis of aerial photography, LiDAR surfaces, ground truthing investigations and geomorphology interpretations as well as hazard identifications presented on a sub-zone basis at scales of 1:10000. Chapter 3 covers the southern zone of the field area and Chapter 4 covers the northern zone.

- **Chapter 5** consists of an in depth study of four sites identified as being particularly hazardous based on historical engineering reports and observations from Chapters three and four. It provides a close up look at the sites at scales of 1:3000 with interpretations of subsurface geometry and landslide processes provided based on LiDAR morphology.

- **Chapter 6** provides and overview of the impacts that the hazards identified in previous chapters will have on the highway and evaluates if avoidance or mitigation can be feasibly undertaken.

- **Chapter 7** summarises the findings of the thesis and provides recommendations for future research.

Chapter 2

Terminology,LiDAR survey Data Processing and Interpretation Methodology

2.1 Introduction

The first part of this chapter provides information on the terminology used when referring to surface units and slope processes as well as the reasoning used in associating the LiDAR model surface morphology with that of surface units. The second section of this chapter details parameters of the LiDAR survey and processing of the raw data as well as the processes involved with digital terrain model (DTM) generation. The final section outlines to methodological approach used for the large scale geomorphology and hazard identification as well as the engineering geomorphological investigations.

2.2 Terminology Used in LiDAR Interpretation

Bedrock and regolith are two broad terms used here to describe the major surface units present on a slope, with regolith being further divided by its mode of emplacement. When interpreting surface units from the LiDAR model in the Haast Pass bedrock refers to exposures of bare schist at the surface, or so close to the surface that the dominant surface morphology reflects the structure of the underlying bedrock. Regolith is a general term used to describe all superficial and unconsolidated materials at the Earth's surface (Matthews and Bridges 2001) and on hillslopes is commonly comprised of mechanical or chemically weathered rock debris formed either in-situ or transported (Goudie 2004). Regolith in the study area have been further subdivided into colluvium and alluvium. In this study the term colluvium is specifically used when referring to material transported and deposited on slopes through mass movement and slope wash processes often with material sourced from the weathering of bedrock (Goudie 2004). When the term alluvium is used it refers to material deposited by flowing water in river valleys often consisting of stratified gravels, sands, silt and clays, depending on the environmental context at the time of deposition (Goudie 2004); While some controversy surrounds the use of alluvium in this way for the propose of describing the origins and material properties the definition provided above has been adopted. Throughout the rest of this document references made to bedrock and regolith use the definitions provided above with regolith only differentiated into colluvium and alluvium if direct observations of the material can be made through ground investigations or aerial photography.

Terminology used in the description of mass movement processes follows the new classification scheme developed by Hungr et al. (2013)(Table in Appendix B) that acts as an update to the widely used Varnes (1978) classification scheme. In this thesis the most commonly used mass movement terms used include rockfall, debris sliding and debris flows with definitions from Hungr et al. (2013). Rockfall processes are defined as, falling, rolling and bouncing of rock with little interaction between mobile fragments. Debris sliding is defined as a sliding mass of granular material along a shallow planar failure surface, typical parallel with the ground surface with the sliding mass usually composed of colluvium. Debris flows are very rapid surging flows of saturated debris normally along established pathways. Throughout the thesis reference to mass movement processes refers to the definitions provided by the landslide classification developed by (Hungr et al. 2013). The terminology used to describe actual features of landslides follows the landslide features definition developed by Cruden and Varnes (1996) and is provided in Appendix C.

When describing the activity of various mass movement processes on slopes a set of three classifications are used including dormant or inactive, recently active and active. Evaluating the activity of mass movement processes on slopes is done by observing the disturbances in vegetation type and density visible in aerial photography with the assumption that large disturbances are a result of mass movement processes; a safe assumption to make given that in the environment of the Haast Pass mass movements are the dominant processes controlling the landscape. Dormant/inactive slopes are defined as slopes consisting of mature vegetation commonly consisting of large trees and a dense tree canopy as is visible in Figure 2.1A. Areas of the slope that have been subjected to landslide activity recently but show signs of vegetation regrowth generally consist of young undergrowth/scrub but lack dense mature tree canopy (Figure 2.1B); Areas classified under the recently active definition have generally been active in the last few decades. Areas considered to be subjected to active processes show clear indications of ongoing mass movements with fresh landslide debris and no vegetation regrowth visible (Figure 2.1C). These active area have in most cases been subjected to landslides in the last few days to months time-scale. While the way that activity has been defined lacks accurate age determination it provides a useful qualitative indicator of the last time the slope was subjected to mass movement activity.

2.3 Differentiating Between Bedrock and Regolith using LiDAR model textures

The key to differentiating between bedrock and regolith surfaces is recognition of the distinctive visual appearance that characterises their surface morphology. Slope surfaces composed of bare rock have morphologies controlled by the resistance of the rock rather than the slope processes acting on them, particularly in hard rock (Selby 1985). It follows that bare rock morphology should be strongly influenced by prominent bedrock structures and can be particularly evident in rocks with a dominant and persistent linear structural weakness, such as bedding or foliation. Due to the nature of regolith being composed of unconsolidated rock debris and particularly with colluvium covering hillslopes consisting of material sourced from mass movement and slope wash processes the resultant morphology will reflect the unsorted and non-bedded nature of the material (Goudie 2004,

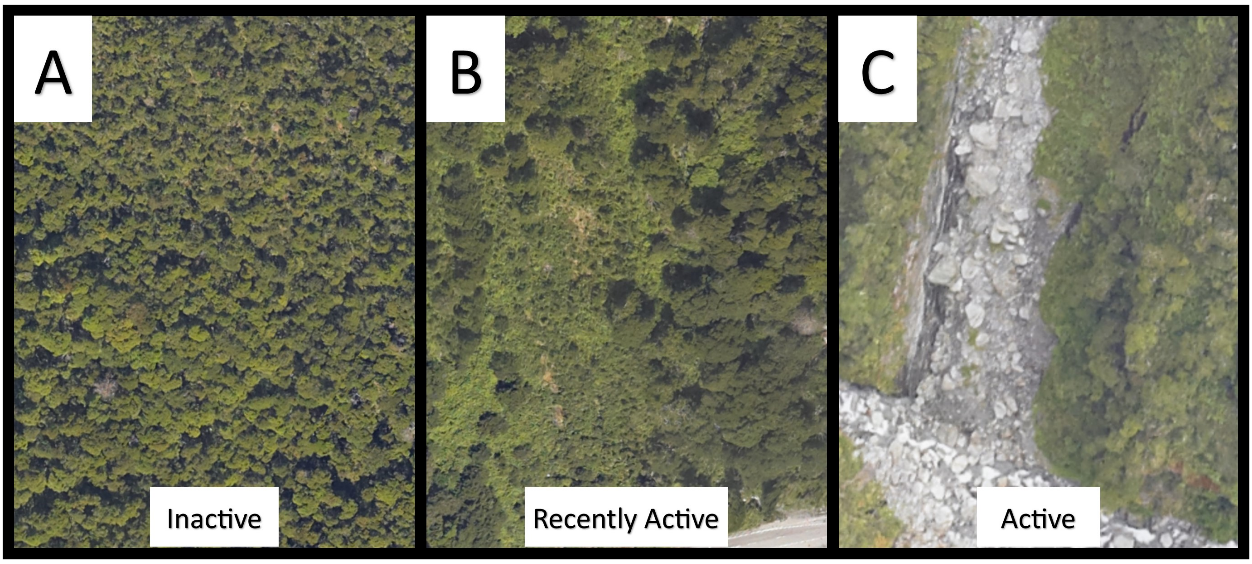

Figure 2.1: Qualitative definition of the state of activity of mass movement processes on slopes inferred from aerial photography. A) No evidence of recent landslide activity with mature vegetation covering the entire area; Area considered to be dormant but may have not have been subjected to mass movement activity for a significant period of time. B) Recent mass movement indicated by the young vegetation inferred to be regrowing after a landslide event; In this specific case the young vegetation was removed by a landslide in the 1970's with the aerial photo taken in 2014 showing the level of regrowth that has taken place. Slopes such as these are considered to have not been active for last few decades but have been subjected to failure. C) Active mass movement processes inferred from direct observations of landslide activity; Likely have been active in the previous months to years.

Selby 1985); As a result the morphology of the regolith covering the slopes should appear to be irregular, rough and lack any persistent or regular structures visible at typical LiDAR mapping scales.

The distinctive morphological differences between bedrock and regolith dominated surfaces is also reflected in the LiDAR model in the Haast Pass. The in-situ schist rock of the Haast Pass has a very pronounced persistent rockmass defect in the form of foliation; Since the surface morphology reflects the underlying rock structure it follows that areas dominated by un-situ schist in the Haast Pass should have morphologies strongly influenced by schist foliation. As Figure 2.2A illustrates, initial observation of the LiDAR model reveal that this is the case with strong linear and persistent undulations in the surface parallel to foliation visible in many areas making identification of bedrock surfaces straightforward. Since nearly all regolith material covering the slopes is likely to be colluvium lacking sorting, bedding or large scale regular persistent structures its appearance in the LiDAR model should reflect this; As Figure 2.2B shows, this is the case with regolith surfaces appearing in the LiDAR model as rough, irregular and generally lacking linear persistent structures with the exception of features formed as a result of slope processes such as streams or rivers.

Ground truthing of selected sites to test interpretations is essential to check if the assumptions being made in the interpretation of the LiDAR model are accurate. Ground truthing is required to confirm that the surfaces identified as bedrock and regolith in the LiDAR model actually are representative of what really exists in the field. Ground truthing also allows closer observations of the regolith enabling information of the materials origins and likely processes that deposited it to be recognised. Given the large size of the field area and the difficulty with traversing the densely vegetated areas the investigation approach required a targeted investigation methodology. Ground truthing first consists of forming initial geomorphological interpretations of what materials

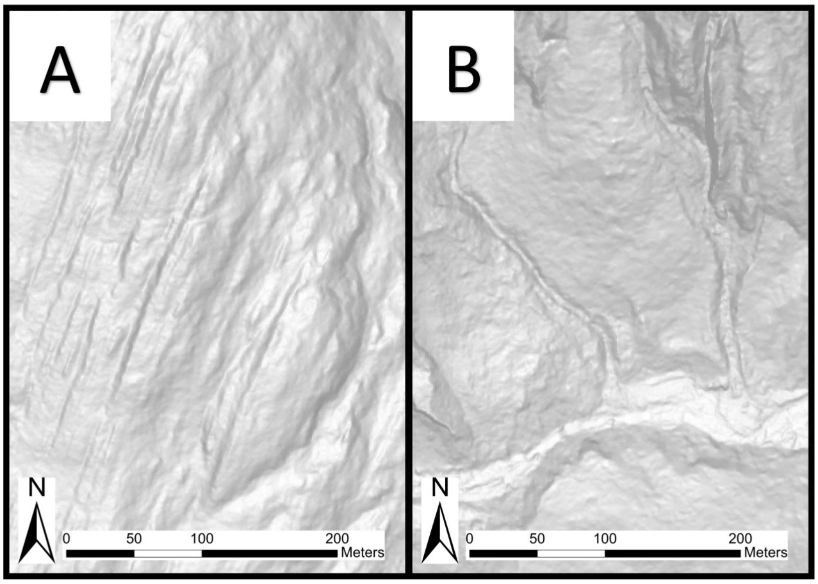

Figure 2.2: Examples of the morphological appearance of bedrock and regolith in the LiDAR model. A) Bedrock surface with morphology controlled by the dominant rockmass defect in schist which is foliation. The regional bedrock foliation strike taken from the regional geological map indicates a strike of 020 degrees, correlating with the parallel undulations visible in the image. B) Regolith surfaces appear rough, irregular and lack any structure. Most of the regolith in the image consists of colluvium with the bright area indicating a stream channel filled with alluvium. Also note a small area of bedrock in the upper right corner of the image.

cover and processes are present and have acted on a slope as well as confirming the causal links between the morphology observed in the aerial photography/LiDAR model and the actual surface units. From these initial observations a site investigation plan is developed that consists of picking sites within the field area, predicting what material and processes were active and then travelling to these sites to observe and identify the materials present. In this thesis the ground truthing of LiDAR interpretations is included in the geomorphological analysis chapters (Chapter three and four) with the locations selected based on identifying different surfaces and features, but restricted to accessible areas where it was safe to travel through.

2.4 LiDAR Survey and Data Processing

2.4.1 Haast Pass LiDAR Survey

The aerial survey for the Haast Pass was undertaken by New Zealand Aerial Mapping (NZAM) between the 19th of December 2013 and 10th January 2014, and consisted of the collection of LiDAR data as well as aerial photography. The purpose of the survey was to generate a bare land surface model of the ground beneath extremely dense vegetation; This necessitated the design of the survey to have a much higher resolution than most standard LiDAR surveys undertaken in New Zealand. The information on the specifics of the survey are taken from the metadata report by New Zealand Aerial Mapping[NZAM] (2014). The surveyed area encompasses the slopes above the highway for a distance of 11km between the Haast Pass Summit and Thunder Creek Falls, 1.5km downstream of the Gates of Haast highway bridge (Extent of LiDAR survey shown in Appendix D). The LiDAR data was collected using NZAM's Optech 3100EA LiDAR system with the aerial photographs collected at the same time as the LiDAR survey using a Trimble AIC aerial photography camera.

Due to the large variability of the topography in the survey area with heights ranging from 200m to 1400m above sea level, necessitated the survey to be flown at 1800m above the lowest ground height of each flight line to maintain adequate clearance. The LiDAR sensor scan angle was set to 12 degrees, the outbound laser pulse rate was set to 50kHz and the mirror scan frequency was set at 31Hz. The flight lines were flown with a minimum overlap of 70% and each flight line was flown twice to increase the point density per square metre. This was designed to give a total of 3.4 points per square metre on open ground but due to steep topography and planning of the survey relative to the lowest point the point density on the open mountain tops are as high as 10-12 points per square metre. With a flight height of 1800m above the ground sample distance of the aerial photography is 0.25m. The GPS base station used during the acquisition of the LiDAR data was referenced to Land Information New Zealand (LINZ) geodetic mark 6731 and ground point check sites were gathered by Opus International Consultants to calibrate/quality check the LiDAR model. The raw data from the LiDAR survey consists of tens of millions of points in 3D space that need to be processed.

2.4.2 Raw Data Processing and Ground Point Cloud Generation

Raw data processing was undertaken by NZAM as part of the LiDAR survey contract with the goal being the creation of a ground point cloud with vegetation removed. The aircraft position and orientation data was combined with the LiDAR range files to generate an unclassified point cloud in NZTM projection using Optech LiDAR Mapping Suite software (New Zealand Aerial Mapping[NZAM] 2014). The unclassified point cloud was then processed to remove vegetation using automated routines in TerraSolid LiDAR processing modules TerraScan and TerraModeler (New Zealand Aerial Mapping[NZAM] 2014). The aerial photographs were developed into 8bit TIFF images and were then draped over the 3D model of the survey area to correct for topography resulting in a series of orthophotos (New Zealand Aerial Mapping[NZAM] 2014).

Table 2.1: Ground Point Cloud Information

Nature of Area	Area (km-2)	No. of Points	Average Point Spacing (m)
Above Tree line	0.346	1170753	0.54
Thin Vegetation	0.346	269818	1.13
Thick Vegetation	0.268	86759	1.76

The output of the raw data processing, provided by NZAM, was a classified point cloud containing ground points that were then used to create the 3D ground surface model. The ground point cloud is provided in a series of 72 individual tiles in .las format and contain a total of 16,606,543 points with vegetation points removed. The density of the ground points in the survey area is quite variable and can be observed as directly related to the density of vegetation. Table 2.1 summarises representative areas of the ground point cloud where a particular density of vegetation is present. In areas where vegetation cover is absent the average point spacing of ground points is 0.54 metres and can be seen visually as the very dense red areas in Figure 2.3A that correlate with the bare ground surface in Figure 2.3B). Average point spacing for areas of thin vegetation cover where vegetation cover is present but not very thick, such as annotation 1 in Figure 2.3B, is 1.13 metres. In areas where vegetation is extremely dense, such as annotation 2 in Figure 2.3B, the spacing of ground points opens out to 1.76 metres. This variability in the ground point cloud needs to be considered when performing the interpolation to create the 3D digital elevation model (DEM).

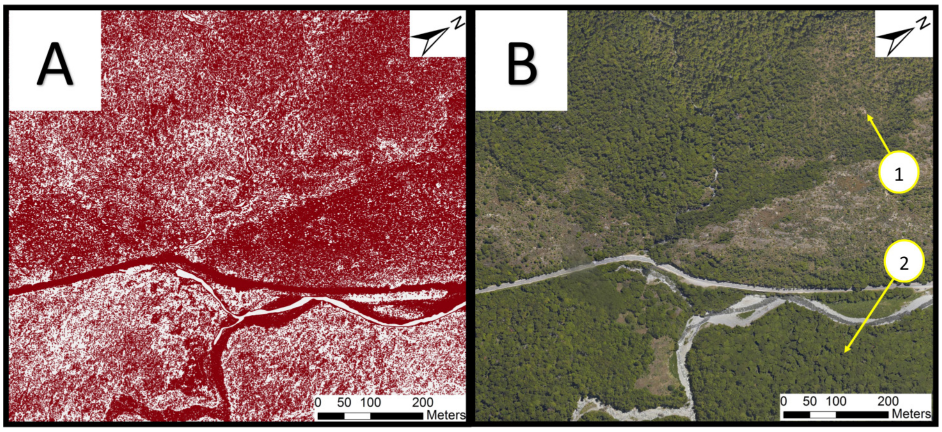

Figure 2.3: A) Ground Point Cloud. The red area consists of red dots each representing a ground point. Note that the continuous white areas just below the highway is the Haast River that does not have any points as the laser energy is absorbed. B) Aerial photograph of the same area as the ground point cloud image. Note the highway running north to south through the image from left to right. 1 = area of thin vegetation. 2 = area of thick vegetation.

2.4.3 Ground Point Cloud Interpolation and DEM Creation

In order to transform the individual points of the ground point cloud into a usable DTM interpolation needs to be performed. Interpolation is the process of predicting the values of a grid of cells based on the value of the adjacent data points, in this case the ground point cloud. Determining the value of the cell size for the interpolation is important in order to produce the best surface without generating terrain artefacts. The choice of interpolation methods is important in order to not smooth out the surface details or introduce artefacts and a process of trial and error was implemented testing three different interpolation methods; Inverse Distance Weighting(IDW), Natural Neighbour and Kriging. The resolution for the surface was set at 2m based on measurements of the ground point cloud in Table 2.1 with a maximum of 12 points or a 20 metre radius used during the interpolation process. The resulting surfaces were all broadly similar due the very high resolution of the ground point cloud and magnitude of the features being studied but the Natural Neighbour interpolation method gave the clearest surface with the least artefacts. The final surface generated was of very high quality and is a significant improvement over the national 25m DEM based of the 20m contours on the topo50 map series. A comparison between the national 25m DEM and the Haast Pass LiDAR derived DEM is shown in Figure 2.4 and highlights the detail with which the surface can be mapped.

2.5 Designation of the Northern and Southern Zones Field Zones

During the initial large scale geomorphology interpretation and slope hazard identification of the field area it became clear that the overall morphology, slope processes and slope hazards changed distinctly in the area around Pipson Creek. South of Pipson Creek the slopes above the highway

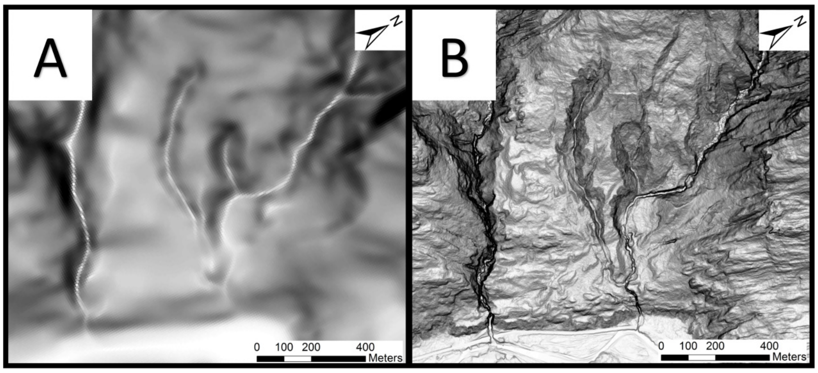

Figure 2.4: Comparison between the national 25m DEM and the Haast Pass LiDAR derived DEM. A) National 25m DEM based on the New Zealand Topo 50 map series 20m contours. B) LiDAR derived DEM for the Haast Pass with a 2m resolution based on the interpolation of the ground point cloud.

are generally less steep, dominated by bedrock surfaces, have active slope processes largely confined to tributary valleys and the Haast River confined to a 50-100 metre wide alluvial plain. North of Pipson Creek the slopes are steeper and many appear covered in varying thicknesses of regolith; Many of the regolith and bedrock slopes in this area show signs of active landslide processes acting on slopes both above the highway and below it where the Haast river is confined to a narrow highly erosive channel. This distinctive morphological, process and river form differences between the two areas is the reason that these areas are presented separately in their own respective chapters. As a result the total field area is divided into the northern and southern zones with the exact boundary shown in Figures 3.1 and 4.1.

2.6 Methodology for Large Scale Geomorphology and Hazard Identification

Identification of the large scale geomorphology and slope hazards is primarily undertaken using high resolution LiDAR in combination with more traditional geomorphology investigation tools to supplement and improve the accuracy of the interpretations. The LiDAR model is generated from the ground point cloud as described in the previous section and subsequently interpreted using ArcGIS software to create the map and ArcScene software to better visualise the surface in 3D space. The process allows the mapping of surface units, identification of landslides and slope hazards at a resolution not previously possible and in areas that are otherwise obscured by vegetation and inaccessible. The method does provide a very high resolution surface, but care needs to be taken throughout the interpretation to avoid the influence on isolated processing artefacts. The effect that processing artefacts could potential have is minimised by making interpretations based on visual morphological trends over several to tens of meters where individual errors have less of an influence. The step by step procedure followed to identify the large scale geomorphology of the field area that is used to evaluate the potential slope hazards is provided below with illustrations of each step shown in Figures 2.5 to 2.9.

Step 1) Aerial Photo Analysis

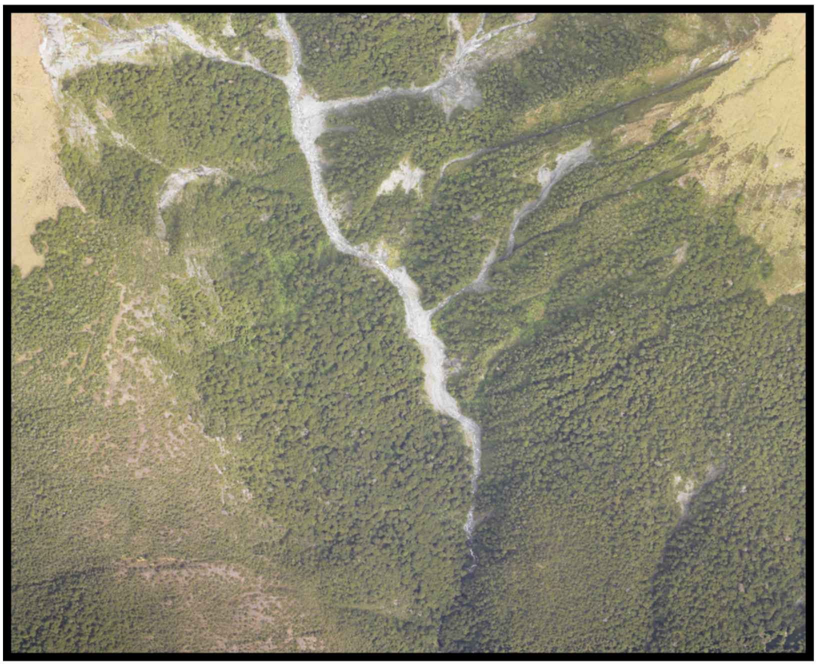

Figure 2.5: While much of the Haast pass is covered by dense vegetation it is still possible to gather useful information from aerial photography. Air photo analysis is used to identify surface morphology, surface unit type and identify the active slope processes in areas where vegetation is thin or absent. Where the surface is exposed and surface units are visible the high resolution aerial photograph from 2014 is used to identify the material as bedrock or regolith and if possible further differentiate regolith. The aerial photo also allows areas active slope processes to be identified and can also differentiate between different processes by linking the observed slope processes and the surface units involved.

The aerial photo analysis is the first step taken as part of the geomorphological analysis. The primary goal of this step is to extract as much information from the slope as is possible from aerial photography. The processes involves the analysis the a recent aerial photo survey taken in January 2014 at the same time as the LiDAR survey. The photo is analysed to identify surface morphology, surface unit type, relative activity states and identify the active slope processes in areas where vegetation is thin or absent. The aerial photo can also differentiate between different processes by linking the observed slope processes and the surface units that are visible. This step highlights the lack of information available with traditional methods of investigation as most areas of the pass are covered in vegetation leaving large areas of the slope unable to be investigated. This is where the LiDAR surface analysis enables a better understanding of the nature of the slopes beneath vegetation.

Step 2) LiDAR Surface Analysis

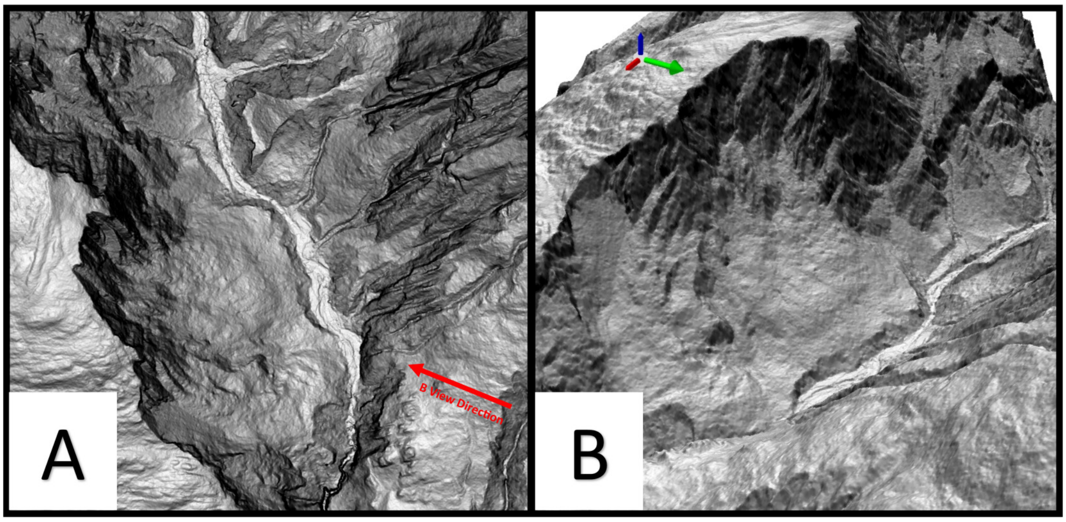

Figure 2.6: For the LiDAR model analysis both a 2D and 3D slopeshade image are used to visualise the surface; A slopeshade has a surface colourised based on the slope angle with all slopeshade images in this thesis showing steep areas a dark shades and flat areas as light shading. Also note that the 3D LiDAR model all have an orientation guide in the upper right corner with a north indicated by the green arrow, blue indicating vertical and the red arrow pointing east horizontally. The LiDAR model is then utilised to identify the different surface morphologies and slope features indicative of mass movement with all vegetation having been removed. Note that Figure 2.5 and 2.6A are showing the same area (Figure 2.5 is a slightly wider aerial view than A above).

The LiDAR surface analysis provided detailed information of the type and distribution of surface units as well as the ability to detect evidence of landslide activity in areas that would otherwise be hidden by vegetation. The LiDAR surface analysis is undertaken using the DTM generated from the ground point cloud provided by NZAM and is visualised in 2D in ArcMap and in a 3D model using ArcScene. For each area being studied an oblique 3D view of the LiDAR model is presented with the surface colourised according to the slope angle (known as a slopeshade surface). This 3D oblique view of the surface can be orientated using the indicator in the top left of each of the images with the green arrow pointing north (Horizontal), the red arrow point east (horizontal) and the the blue arrow pointing vertically (See example in Figure 2.6 B). This 3D surface is then analysed to identify the differing morphologies indicative of surface units as well evidence of landslides. This method of analysis provides great benefits over traditional mapping techniques as it allows large areas obscured by vegetation to be quickly mapped and enables observation areas that would otherwise be inaccessible.

Step 3) Formulation of Initial Geomorphological Interpretations

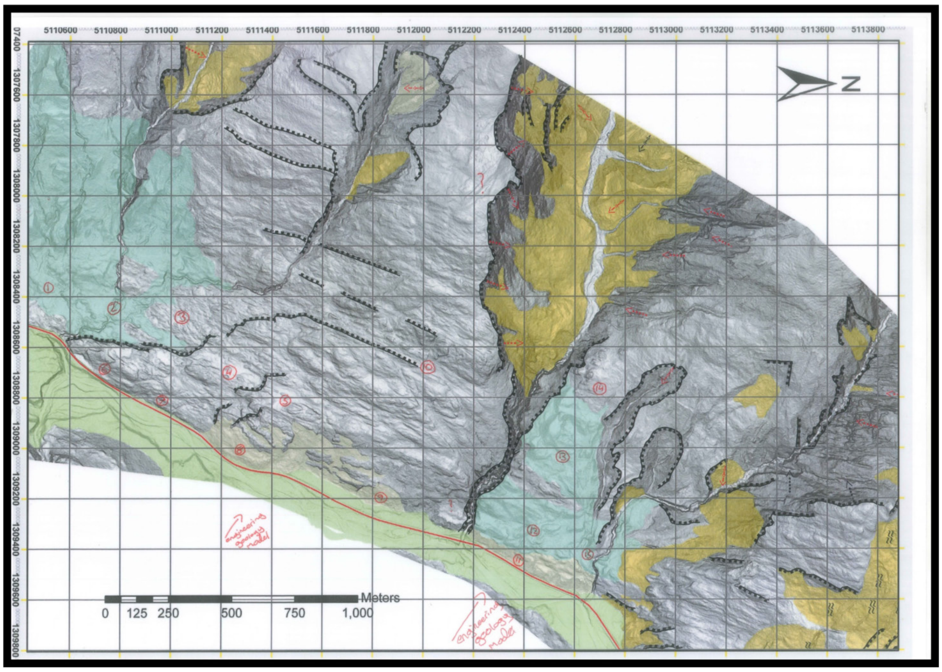

Figure 2.7: Initial geomorphological interpretation map. From the analysis of aerial photography and the LiDAR model, initial geomorphological interpretations are made and applied to a geomorphology map with a LiDAR slope-shade acting as the base image. This map is used as the basis for the ground truthing investigations with sites selected to test as many different interpretations as possible. The initial interpretation shown above is an example of what was produced as a working map and is not included in the thesis. An example of the locations of targeted ground investigations is shown by the red numbers in circles on the map above.

Formulation of initial geomorphological interpretations consists of combining the analysis of the aerial photography and LiDAR surface with the aim of prioritising areas that will be investigated during the ground truthing field work. Initial geomorphological interpretations consist of creating a draft geomorphological map showing the type and distribution of surface units, landslides and slope processes. This map is used as the basis for the ground truthing investigations with sites selected to test as many different interpretations as possible. The initial interpretation shown above is an example of what was produced as a working map and is not included in the thesis. An example map showing the locations of targeted ground investigations is shown by the red numbers in circles on the map in Figure 2.7 (Note this map is not included in the thesis as it is a working draft). Because the size of the field area, dense vegetation and steep terrain make ground investigations difficult and time consuming, the only feasible option is to undertake a targeted ground investigation program; the initial geomorphological interpretations provide the information needed to design an investigation program that can feasibly test as many of the interpretations made in the largest number of settings.

Step 4) Ground Truthing

Figure 2.8: The image above shows one of the ground truthing sites (Site 2 in 2.7) where investigation predicted the presence of regolith, a prediction that was subsequently confirmed. Not all sites that were selected for ground truthing were able to be tested as thick vegetation, steep slopes and very dangerous ground conditions made access incredibly difficult and posed too great a safety hazard.

Ground investigation was critical to test the interpretation that LiDAR surface morphology was a valid method of differentiating between surface units. Investigations consisted of navigating to sites selected in step 3 using a GPS and then searching for an exposure of the surface unit in that area. Finding an exposure was difficult as beneath the vegetation canopy a thick cover of moss covered the ground in the southern parts of the field area and in the north the surface was covered by dense undergrowth and thick deposits of organic detritus (Moss cover can be seen in Figure 2.8). Once a site was located its location was marked on the GPS, a photograph was taken and the exposure was logged. The location of each site is marked on the 3D oblique LiDAR surface for each zone and is referred to as S1 for Site One. Not only does this step serve to test the interpretations made using aerial photographs and the LiDAR surface, but it also served to get a better understanding of the composition of the regolith deposits to provide an insight into the likely regolith sub-type and processes of emplacement. The observations made during the ground investigations are then combined with the aerial photograph and LiDAR surface analysis providing a robust line of evidence with which to develop the final geomorphological interpretations and associated geomorphology map of the zone.

Step 5) Development of Final Geomorphological Interpretations

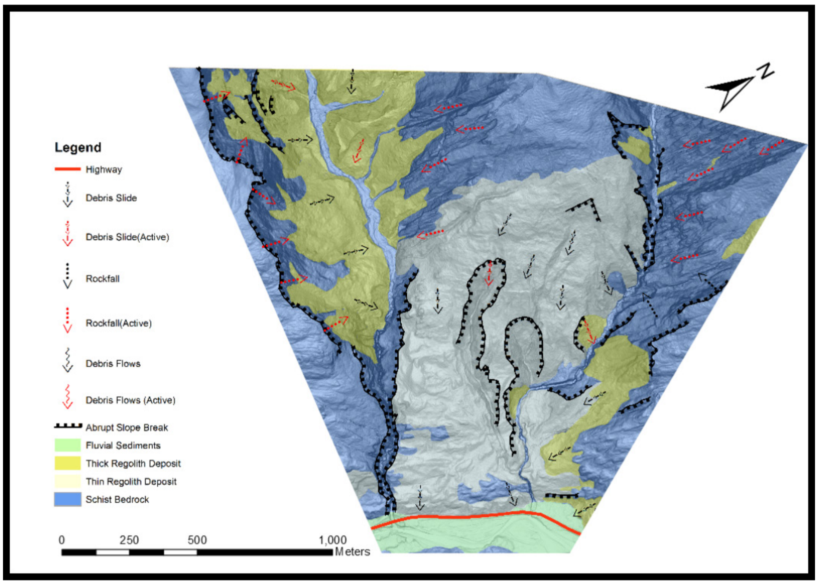

Figure 2.9: An example of the final geomorphology map a Zone showing. Arrows indicate surface processes and are coloured red for active and black for inactive. Surface unit distribution and type is indicated by the coloured areas with blue indicating bedrock, light brown indicating a thin cover of regolith, yellow indicating a thick deposit of regolith and green indicating regolith material that has been sub divided into alluvium. The slope processes symbols used are a modelled on the GMK mapping key digitised by Otto and Dikau (2004). The digitised key is freely available from (http://www.geomorphology.at/symbols.html) and used within this study with permission

Final geomorphological interpretations are made by combining the aerial photo analysis, LiDAR surface analysis and information from the ground truthing investigations to identify the distribution of surface units and the active or inactive processes. This step also involves the creation of a geomorphological map of the zone showing the distribution of surface units and surface processes over a base image of the LiDAR slopeshade of the zone. The mapping key uses colours to distinguish between surface units and arrows to denote surface processes that are coloured red for active and black for inactive. The slope processes symbols used are a modelled on the GMK mapping key digitised by Otto and Dikau (2004). The geomorphological interpretation is an important step as it serves as the basis for the evaluation of the slope hazards that the highway is exposed to.

Step 6) Identification of Slope Hazards

The purpose of the slope hazard identification section is to interpret how slope processes and the highway alignment interact to create slope hazards. The geomorphological map is used to identify the areas where slope processes and the highway may interact and have either a direct or indirect impact on the highway. The hazards are presented in a bullet pointed list with a short comment on the reasons that the slope process is a potential hazard and a comment on the magnitude of an event. This serves to identify the areas that are hazardous with the most hazardous areas identified further investigated in detail as small-scale engineering geomorphology investigations in chapter 5. The potential landslide hazard scenarios are also discussed further in the context highway management implications in chapter 6.

This methodological approach provides a robust way of evaluating the geomorphology of the slopes above the highway that is required to provide a much clearer picture of the hazards that the highway is exposed to. The total field area consists of 16 square kilometres of largely inaccessible slopes predominantly covered by dense vegetation. The method described above allows the entire 16 square kilometres to be mapped quickly (by an experienced engineering geologist or geomorphologist), safely and provides an unmatched level of detail with which to inform the hazard analysis. While a survey such as the one undertaken in the Haast Pass can cost upwards of $100,000 and at first may seem like an excessive amount of money to spend on corridor investigation; in reality it is a very high value and relatively low cost investigation tool when the coverage area and accuracy of the produced maps are considered. One of the other advantages of this method is that it can inform on the areas that need to be investigated further and provides the detailed information with which to prioritise and design more detailed investigations.

2.7 Methodology for Engineering Geomorphology Investigations

The aim of the engineering geomorphology investigations is to apply the new insights that the high resolution LiDAR survey can provide to study a number of small sites in very high detail. The sites to be investigated are selected from areas that either pose the greatest apparent hazard to the highway, due to large areas of instability or historic instability, or landslides that have no history of instability that appear to pose a hazard to the highway. At each site the LiDAR model and aerial photography area used to map the distribution of surface units and landslide features onto a engineering geomorphology map. This new information in combination with previous observations or subsurface information is combined to generate a slope subsurface interpretation and identify the landslide processes active within the investigation area. The investigation workflow undertaken at each site is outlined in more detail in Figures 2.10 to 2.13 with specific information on each step discussed in the captions below each image.

Step 1) Small-scale 3D LiDAR Surface Analysis

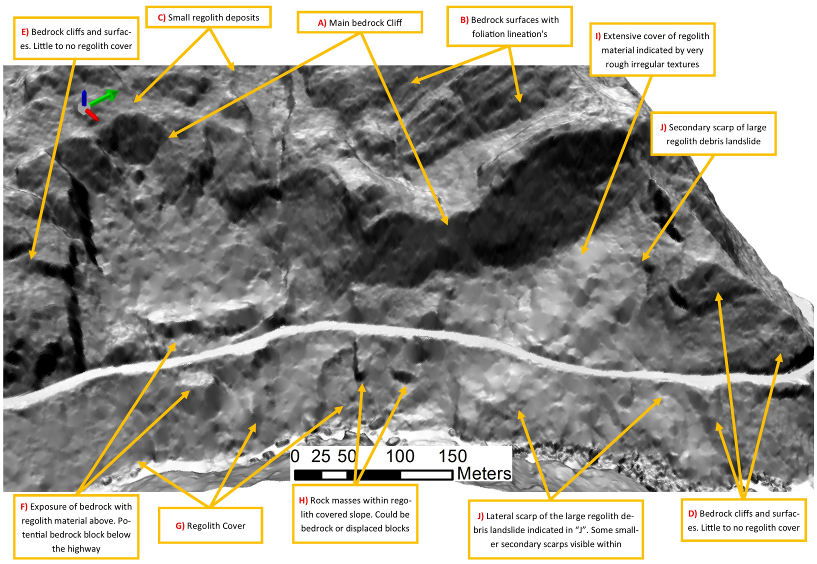

Figure 2.10: The first step in the small-scale engineering geomorphology investigations is identification of surface units and landslide features. This is done through analysis of the LiDAR model in 3D combined with observations of materials and landslide features visible in aerial photography although aerial photography is rarely helpful at this scale. The key features of the analysis are then indicated on in a 3D annotated image of the LiDAR model as shown above.

Step 2) Development of Engineering Geomorphology Map

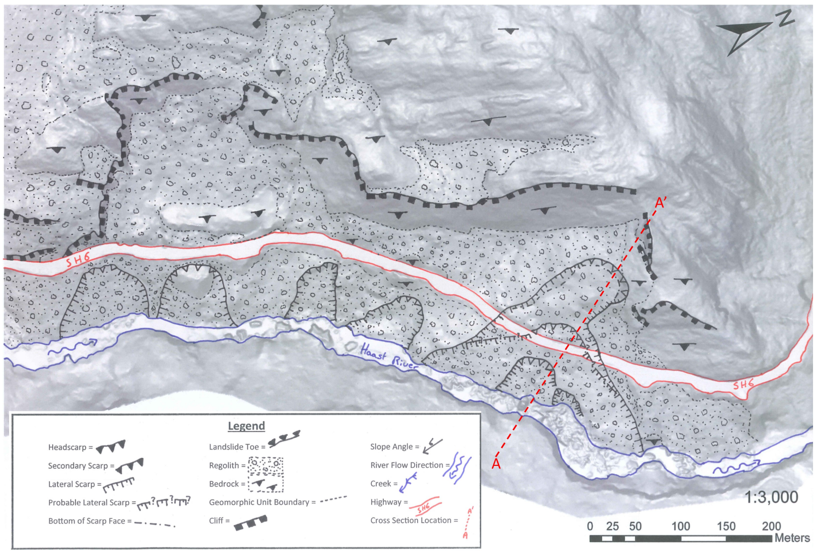

Figure 2.11: The 3D LiDAR model interpretation is used to create an engineering geomorphology map showing the distribution of bedrock and regolith surfaces as well as the location and persistence of landslide features. Engineering geomorphology maps are hand drawn over a LiDAR slopeshade surface of the investigation site and a combination of the 3D LiDAR model and the map are used to discuss the origins and behaviour of the sites.

Step 3) Slope Subsurface Interpretation

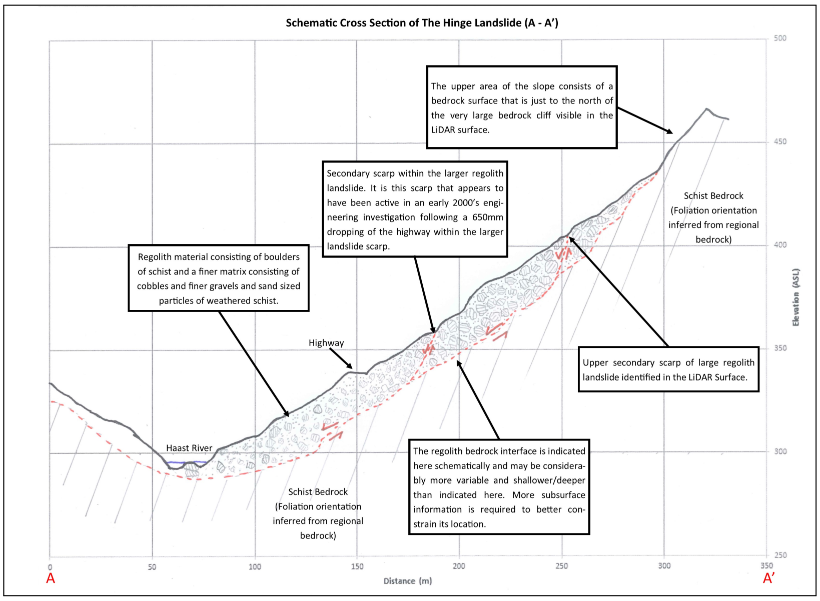

Figure 2.12: The new information from the LiDAR model combined with previous investigation information are then combined to generate an interpretation of the subsurface conditions at each of the sites. The cross sections use the LiDAR model as the ground profile with extrapolations below ground based on the overall surface morphology and observed landslide features. This section aims to give a reasonable interpretation of the below ground conditions that fit with the observed surface units, surface morphologies, and identified landslide features primarily serving to highlight the need for further investigation at most of the sites.

Step 4) Interpretation of Landslide Processes and Present Slope Stability

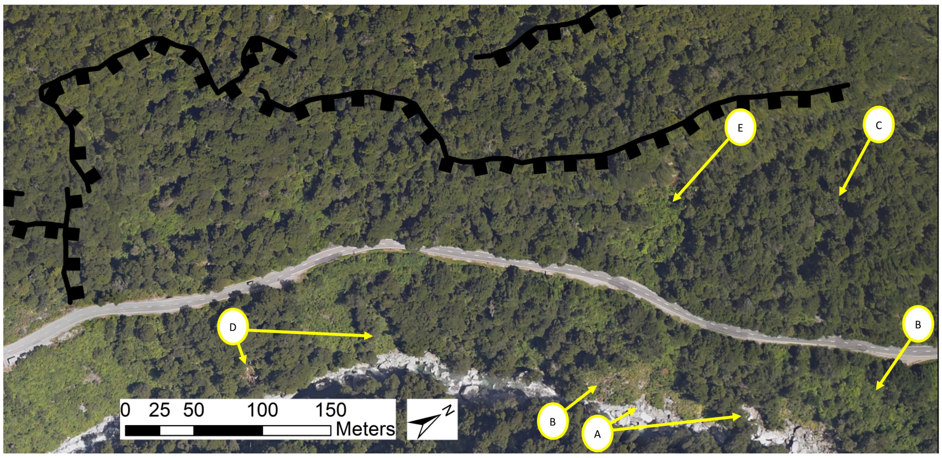

Figure 2.13: With information taken from the LiDAR model, aerial photography and the subsurface interpretation of surface units and landslide features the landslide processes acting on the slope are interpreted. A bullet pointed list of the slope processes thought to be acting on the slope is provided along with the origin and likely behaviour and potential triggers. This information along with the interpretations made previously are then used to give an assessment of the future development of the site along with recommendations for further investigations to fill the gaps in understanding.

The methodology for the small scale engineering geomorphology investigations provides the big picture overview for hazardous and inaccessible sites. The ability to map the distribution of surface units and identify landslide features unrecognisable from the ground in high detail beneath vegetation is a valuable tool in understanding the potential hazard. Identification of the surface units and landslide features also allows interpretations of the subsurface to be made, but obviously the interpretations area subject to a high degree of uncertainty without direct subsurface information. Just as the large scale methodology in section 2.6 was able to provide information on the sites that could be the most hazardous; the small scale engineering geomorphology investigation methodology provides an interpretation of the behaviour of the hazardous slopes and provides the detailed information that can be used to design a cost effective site investigation aimed at refining interpretations.

Chapter 3

Southern Zone Geomorphological Analysis and Slope Hazard Identification

3.1 Introduction

This chapter provides and analysis of the slopes above the highway in the Southern Zone defined as the area between the Haast Pass Summit and the Pipson Creek fans (Extent in Figure 3.1). The chapter aims to identify geomorphic units and both inactive and active slope processes on the slopes above the highway and subsequently identify the potential landslides hazards the highway is exposed to. In order to identify the geomorphic units and slope processes a combination of aerial photo analysis, LiDAR model analysis and targeted ground investigations are used to generate a map of the hillslope geomorphology for slopes above the highway. The map is then used as the basis for the landslide hazard identification with the more hazardous slopes investigated further in the detailed slope investigation chapter (chapter 5).

3.2 Sub-Zone Segmentation

The Southern Zone has been divided into three sub zones based on the combination of geomorphic units and processes observed on the slopes. The three zones consists of the slopes between the Summit of the Haast Pass and Wilson Creek, slopes between Wilson Creek and Robinson Creek and finally the slopes between Robinson Creek and the Southern Pipson Creek Fan. The location and names of the features that break up the Southern Zone are shown in Figure 3.1 and should be used to locate and orientate the section.

3.3 Summit to Wilson Creek

3.3.1 Aerial Photo Analysis

Identification of surface units and slope processes is possible with aerial photography, but as most of the zone is covered by dense vegetation the extent that can be identified is limited. The most obvious features are four parallel lineations running approximately north to south (Figure 3.2 A). Three of the lineations can be observed in the more densely vegetated areas where variations in the tree canopy are representative of the sharp changes in the topographic surface below (Figure

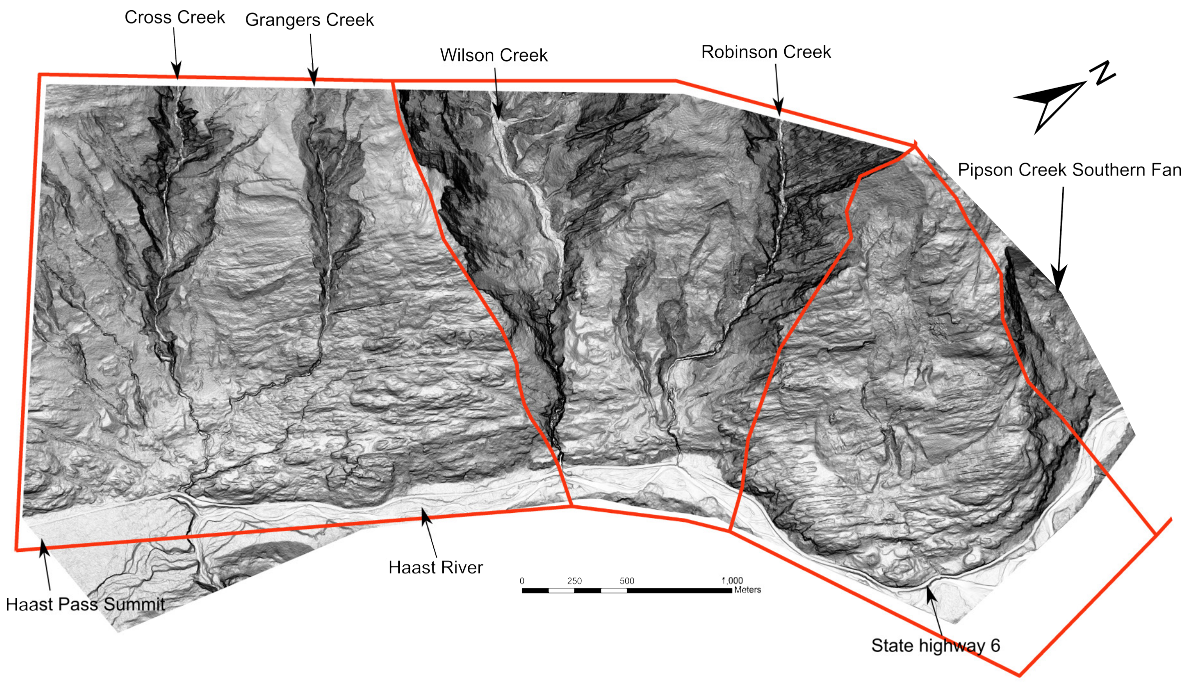

Figure 3.1: Breakup of the southern zone with sub-zones outlined by the red boxes and named from left to right as; Haast Pass Summit to Wilson Creek, Wilson Creek to Robinson Creek and Robinson Creek to Pipson Creek Southern Fan.

3.2 B). Immediately below the four parallel lineations is an area of hummocky topography with the top of the hummocks lacking vegetation (Figure 3.2 C). The hummocky area can be seen extending down slope from the lineations to the dense vegetation directly above the road (Figure 3.2 C lower arrow). To the south of the hummocky area sections of the slopes above the highway completely lack vegetation and the surface visible is coloured light brown to grey (Figure 3.2 D). In all other sections of the zone, including all slopes next to the highway, dense vegetation obscures the ground surface, preventing identification from aerial photography.

Evidence of active slope processes are visible on some parts of upper slopes above Grangers Creek. The slopes above the creek are covered by dense vegetation with the exception of one area where density varies (Figure 3.2 E) and another where vegetation is completely absent (Figure 3.2 F). In the area of variable vegetation density it is possible that mass movement processes have resulted in a loss of vegetation and a reduction in density compared with surrounding areas. An example of what this may look like is visible on the same side of the creek just upstream (Figure 3.2 F). This area lacks any vegetation and does not appear to be an exposure of bedrock. The light coloured material is almost certainly a veneer of regolith over bedrock that has been exposed by a debris slide involving movement of the top cover of regolith and the vegetation.

Slope processes are visible in parts of Cross Creek and have resulted in the removal of vegetation exposing bedrock and regolith. Bedrock exposures can be seen in the creek bed and streams running into the creek in the upper reaches (Figure 3.2 G). Small exposures of regolith are visible on slopes on the true right side of the creek in the upper section of the creek (Figure 3.2 H) as well as larger exposures (Figure 3.2 I) just before the creek enters a narrow dark steep sided channel. Regolith is only exposed at the toe of slopes where river incision has resulted in destabilisation of the slope that has then resulted in mass movement of the surface materials. It is not possible to

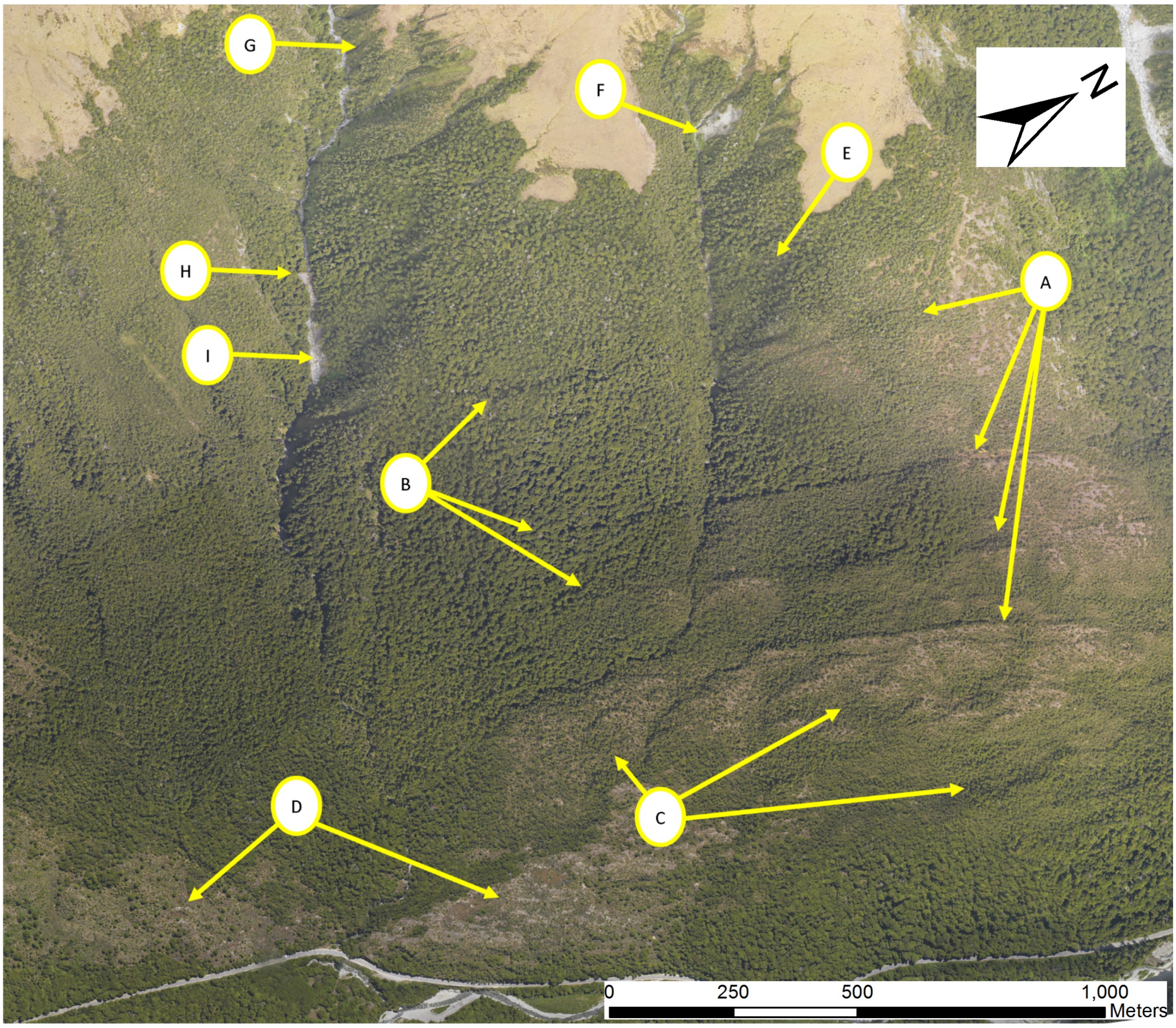

Figure 3.2: A)Foliation aligned lineations (B) Offset tree heights in line with lineations on slopes to the north (C) Area of hummocky topography (D) Area with sparse vegetation that appears to consist of rock (E) Variable density of vegetation (F) Exposed regolith where a debris slide has occurred (G) Bedrock slope with foliation aligned lineations (H) Small exposure of regolith next to stream (I) Exposure of regolith alongside stream.

directly observe the material above the regolith exposures but it can be inferred that the presence of regolith at the base of the slope continues up to the steeper slopes likely composed of bedrock.

3.3.2 LiDAR Surface Analysis

The morphology of the slopes north of Grangers Creek suggests that the surface of the slope is composed of bedrock with the exception of lower portions of slope next to the highway where a combination of bedrock and regolith cover is present. Large magnitude persistent lineations and large hummocks identified in the aerial imagery are visible in the LiDAR surface extending across the entire slope and most of the way down to the highway (Figure 3.3 A). The only area where bedrock structures are not visible the surface of the slope is a section next to the highway in the north of the zone (Figure 3.3 B). In this location bedrock is exposed in isolated bedrock cliffs and small flat areas where bedrock structures are visible (Figure 3.3 C). Between these isolated areas of bedrock a more irregular surface texture consisting of smaller magnitude hummocks is visible (Figure 3.3 B). The material between the bedrock is regolith sourced from bedrock failures further upslope. These regolith deposits appear to be relatively thin given the presence of isolated areas of bedrock throughout the slope.

Between Cross and Grangers Creeks the visible structures indicates bedrock at the surface in the upper part of the slope and small amounts of regolith at the base. This area is completely covered by vegetation as seen in the aerial photo of the zone, however, LiDAR has been able to image the ground surface otherwise obscured by vegetation. The bedrock lineations and foliation orientated hummocks visible to the north are also visible across most of this slope (Figure 3.3 D). The presence of theses features indicates that bedrock is exposed at the surface from just above the confluence of Cross and Grangers Creeks almost to the top of the slope. On the lower slopes bedrock structures are covered by a thin deposit of regolith with areas of bare rock structure confined to an isolated area just above the confluence of the two creeks (Figure 3.3 E). The most significant feature that can be recognised on this slope is the presence of tension cracks at the top of the slope and deformation of the large persistent lineations running across the slope (Figure 3.3 F). These features indicate that mass movement has or is currently taking place on this slope.

To the south of Cross Creek slopes are dominated by a thin cover of regolith obscuring bedrock on upper slopes and results in only small isolated areas of bedrock exposure on lower slopes. Bedrock structures that can be seen on other slopes are absent and the surface appears more uniform and smooth (Figure 3.3 G). This smooth surface is a cover of regolith that extends from the top of the slope down to the confluence of the creeks with only occasional flat steps in slope interrupting the flat surface. It is unclear if the flat areas are exposures of bedrock or remnants of older terrace surfaces, but their very flat planar discontinuous surface is inconsistent with areas of bedrock seen elsewhere. The stream channels running across the regolith appear to be flowing in steep sided channels (Figure 3.3 H) suggesting that the streams flow in bedrock channels indicating that the regolith cover must be thin. Bedrock is exposed in the lower portions of the slope where bare rock structures are visible on the surface (Figure 3.3 I).

The valley sides of Grangers and Cross Creeks are characterised by steep bedrock cliffs and regolith covered bedrock slopes. Bedrock can be recognised by the dark areas at the margins of the creek valleys in Figure 3.3. Below many of these bedrock cliffs the slopes surface morphology consists of irregular rough surfaces similar in appearance regolith material identified next to the highway (Figure 3.3 J). The lower potions of many of the slopes appear to be covered by this regolith texture

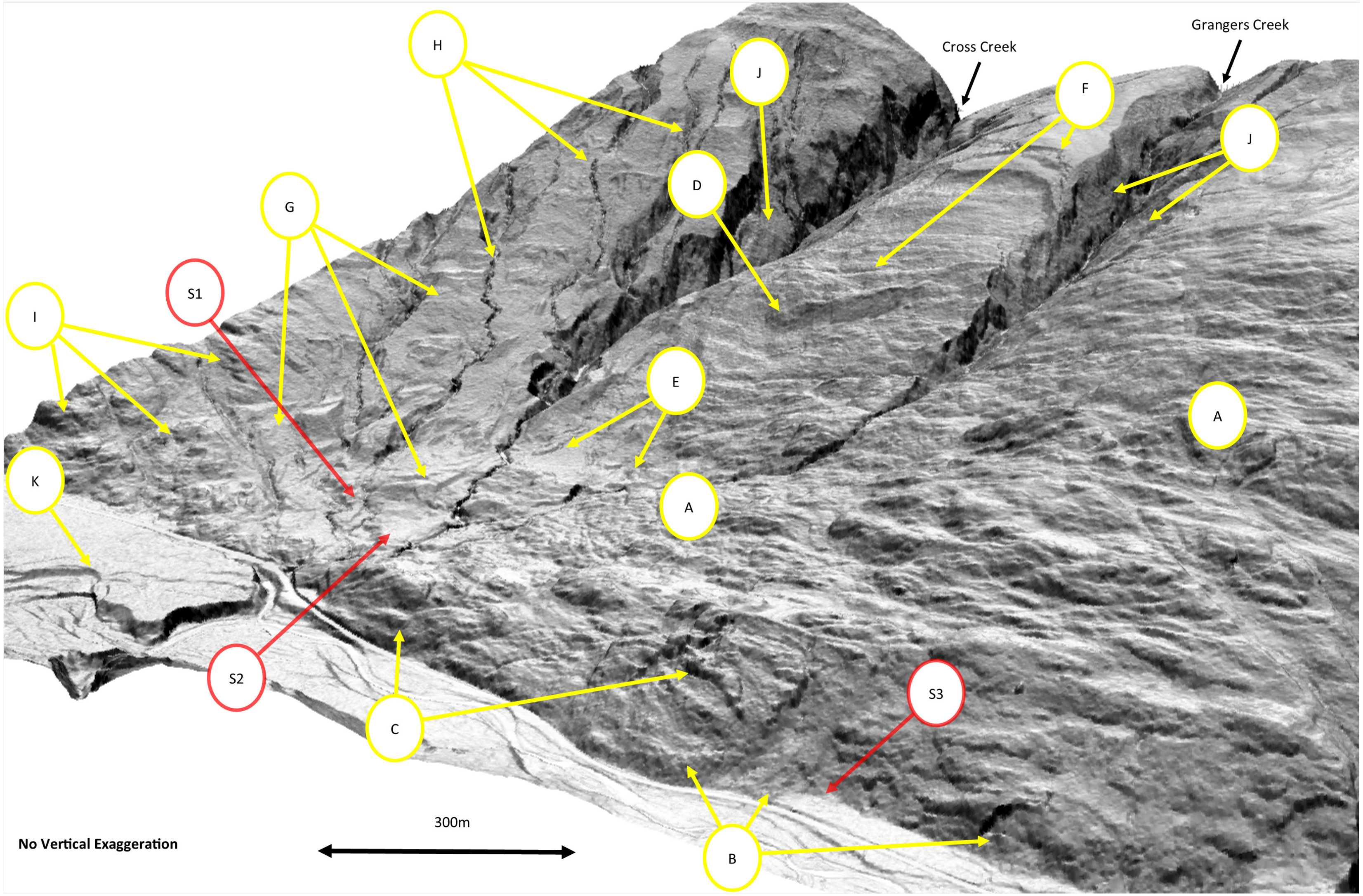

Figure 3.3: Slopeshade image of the LiDAR surface. Light colours indicate shallowly sloping areas with steep areas appearing as dark colours. (A) Bare rock slope (B) Regolith cover (C) Bare rock exposures (D) Bare rock slope (E) Regolith deposit (F) Tension cracks and lineation deformation (G) Regolith covered slope (H) Streams in confined steep sided channels (I) Bare rock exposures surrounded by regolith cover (J) Regolith cover beneath rock cliffs (K) Quaternary terraces at summit of Haast Pass. The red arrows indicate the location of a ground truthing site referred to in the next section (S1= Site 1).

with the material likely sourced from the steep bedrock cliffs above.

3.3.3 Ground Truthing

Site one is situated in an unnamed stream bed that runs across what was interpreted to be a slope covered by a shallow cover of regolith with streams flowing in steep sided bedrock channels. The stream was found to be flowing in a shallow bedrock channel as inferred from the LiDAR surface analysis. A number of small cascades 0.5m to 5m in size were observed in a shallow channel with steep bedrock banks. An example of one of the steep sided channels with a small waterfall is shown in Figure 3.4. On the true right side of this stream a well exposed area of bedrock with foliation planes visible can be seen beneath the overlying regolith (Figure 3.5). Measurements of the foliation orientation indicated a strike of approximately 025 and a dip of between 60 and 65 degrees to the east. These foliation measurements are consistent with the regional bedrock foliation attitude of the area suggesting it is in-situ schist bedrock. The observations are consistent with the interpretations made in the LiDAR surface analysis suggesting that the streams flows in steep sided shallow bedrock channel with the area covered by a thin deposit of regolith.

Figure 3.4: SITE 1a. Stream flowing in a steep sided channel. Schist bedrock is exposed in the stream bed and on the steep sided margins where it is covered by moss. The regolith material begins where the vegetation overhangs the stream above the moss. The location of this site is shown in Figure 3.3 (S1)

Above bedrock the regolith is poorly exposed due to the dense vegetation cover and the only material visible exists near the regolith-bedrock contact. The regolith material above the bedrock consists mostly of unconsolidated coarse sand with with rounded elongate fine gravel making up the matrix with cobbles and small boulders (less than 400mm) also rounded and elongated (NZGS classification scheme). The thickness of the regolith exposed was at least 1.5m before the top was obscured by thick moss and undergrowth, however, based on the LiDAR observations it likely continues above the moss and vegetation to a depth of approximately 2m-3m.

Figure 3.5: SITE 1b. The regolith bedrock contact can be seen at the top of the image. The regolith material consists of coarse sand and rounded gravel with rounded cobbles of schist (Yellow annotation) with a light brown appearance. The regolith sits over schist rock with foliation orientations matching regional bedrock attitudes. The location of this site is shown in Figure 3.3 (S1)

Site two is located on the same slope as site one but is closer to the confluence of Grangers and Cross Creeks. It was expected that this site would consist of regolith at the surface with bedrock several meters below. Figure 3.6 shows a 2m high exposure of material that has been exposed by an overturned tree. The material consists of unconsolidated clasts of schist ranging from highly angular gravels to a mix of angular cobbles/boulders with occasional rounded cobble. The matrix consists of coarse sand with minor amounts silt and is non cohesive (NZGS classification). The material observed at this site supports the interpretation made in the LiDAR model analysis that the area is covered by regolith material. No bedrock was found at the site so the thickness of the regolith at this location was not able to be established.

Site three is located at the base of a what was interpreted to consist largely of bedrock surfaces surrounded by regolith with the location of site 3 on the interface between the slope and an older river terrace(Figure 3.3 S3). A number of very large boulders were found at the base of this slope with one example shown in Figure 3.7. While this boulder is obviously out of place others were not as easily recognized. Further upslope from where the photo in Figure 3.7 was taken a number of very large schist outcrops can be seen beneath the undergrowth. Foliation is visible on these outcrops and measurements showed a wide range of strikes and dips none of which match bedrock foliation, indicating that the slope has been unstable and resulted in the movement of the blocks down slope. The ground investigation supports the LiDAR model interpretation suggesting that the slope is at least partially covered by regolith as it was not possible to identify the bedrock exposures higher up slope.

Figure 3.6: SITE 2. Exposure of regolith beneath an overturned tree (Behind photographer). Material consists of angular gravels and cobbles of schist rock. The location of this site is shown in Figure 3.3 (S2)

Figure 3.7: SITE 3. Schist boulder at the base of a regolith covered slope next to the highway. Many boulders such as this one are present at this location with a wide range of foliation attitudes inconsistent with regional bedrock. The location of this site is shown in Figure 3.3 (S3)

3.3.4 Geomorphic Interpretations

The surface of slopes between the summit of the pass and Wilson Creek are mostly composed of schist bedrock with some areas covered by variable thicknesses of regolith cover (Figure 3.8). The slopes adjacent to the highway consist of schist bedrock in the southern half of this area and a both bare bedrock and regolith cover in the northern half. Slopes to the north of Cross Creek are almost entirely composed of schist bedrock with bare rock structures extending from just above the highway to the top of the slopes. The slope to the south of Cross Creek is entirely covered by regolith with only small areas of the slopes next to the highway composed of bedrock. In Creek valleys the slopes consist of bedrock cliffs and steep slopes with many covered by a thin veneer of regolith obscuring bedrock.

Slope processes, inferred from aerial imagery, LiDAR model and ground truthing sites are shown on the geomorphology map as arrows in Figure 3.8. Active slope processes, shown as red arrows, are confined to the steeper upper creek valleys with rockfall and debris sliding from bedrock cliffs and regolith covered slopes. The presence of bedrock on slopes north of Cross Creek and the lack of regolith cover suggest that the areas has not been subjected to detectable mass movement processes and is unlikely to be subjected to landslides in the future. The bedrock slopes next to the highway in the south of the zone appear to be stable with no significant regolith deposits indicating that mass movement process are likely to be small and localised. The northern section of slopes next to the highway has been subjected to significant mass movements with colluvium covering bedrock and large boulders present at the base of the slope suggesting that debris sliding has taken place in the past, however, the density of vegetation across the slope and particularly on top of many of the boulders suggests that mass movements have not taken place for a significant period of time.

3.3.5 Slope Hazard Identification

From the aerial photo analysis and particularly the LiDAR model analysis it is possible to identify the potential hazard that slope processes may have on the highway. The potential hazards identified include debris sliding, rockfall, debris flows and deep seated landsliding with a discussion on the location and likelihood of each process affecting the highway summarised below:

1. **Debris Slides:** There is the potential for the regolith material identified at the bottom of the slope alongside the highway south of Wilson Creek to be subjected to future debris slides. The area now appears to inactive with little evidence of recent debris slides, but the potential for relatively small debris slide to remobilise the thin regolith cover on the slope still exists. The presence of the highway between the slope and the river in this location is likely aiding the stability of the slope by protecting it from being undercut by the river.

2. **Rockfall:** The presence of steep schist bedrock cliffs and slopes adjacent to the highway in th southern portion of this zone presents a potential hazard from rockfall events. Analysis of rockmass defects on the exposed cliffs indicated that the rockmass has two main defects forming tabular sheets that are released by fractures. Overall the cliffs appeared relatively stable and the size of the blocks released from the faces of the cliffs would be small.

3. **Debris Flows:** The regolith cover on the slope south of Cross Creek was likely deposited

through a combination of debris flows and debris sliding with additional deposition by streams in the flatter areas at the base of the slope. The area now appears inactive and further debris flows appear unlikely. If a debris flow were to occur it would likely remain within the incised stream and creek channels until the large flat region at the base of the slope where it would likely deposit it material before reaching the highway.

4. **Deep Seated Gravitational Failures:** A large area of the bedrock slope between Cross and Grangers Creeks appears to show sighs of rockmass lineation deformation in the LiDAR surface and there also appears to be a headscarp feature at the top of the slope. It was not possible to reach the area during ground investigations to evaluate the are more closely but given the small amount of deformation that has taken place since the slope was de-buttressed after the last glaciation the slope is probably not an immediate threat to the highway. It should, however, be considered to be in an unknown state of activity until confirmed otherwise.

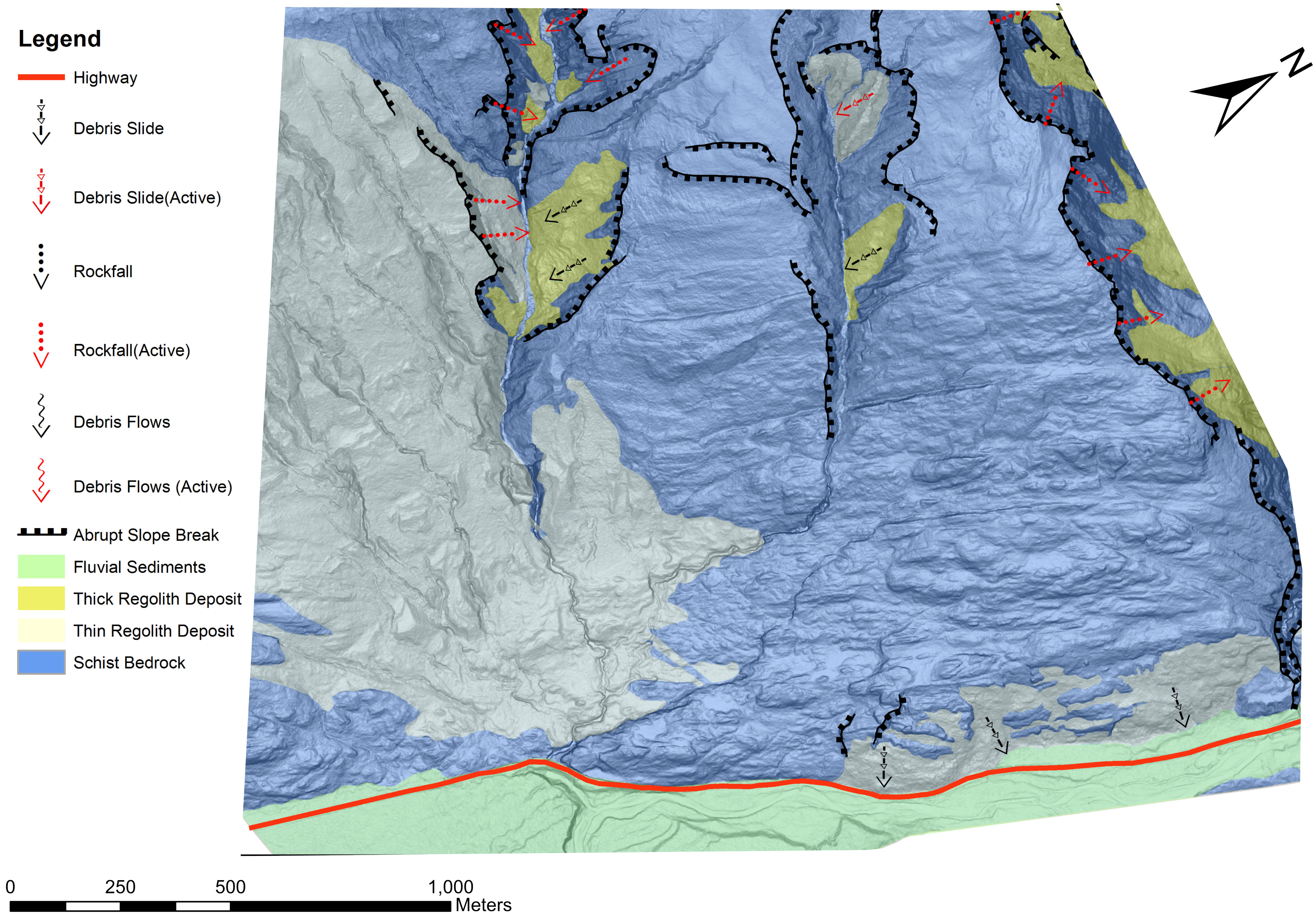

Figure 3.8: Geomorphology of the western hillslope above the highway between the Haast Pass Summit and Wilson Creek. The background image is a hillshade of the LiDAR model with an illumination direction of 300 and an azimuth of 35 degrees.

3.4 Wilson Creek to Robinson Creek

3.4.1 Aerial Photo Analysis

The slopes facing the highway are completely obscured by vegetation except in some small isolated areas where vegetation is absent as a result of what appears to be small landslide events (Figure 3.9 A). In Wilson and Robinson Creek valleys vegetation cover is more variable with some areas covered by very dense vegetation and other areas lacking any vegetation at all. The lack of vegetation is some of these creek valleys makes identification of geomorphic units and interpretation of slope processes possible is some locations.

Bedrock cliffs and steep slopes with large regolith deposits at the base are visible on the slopes on both sides of Wilson Creek. On the south side of Wilson Creek bedrock cliffs can be seen at the top of the slopes with a variable density of vegetation below and appear to be a result of rockfall and debris sliding that has taken place recently (Figure 3.9B). On the north side of the creek persistent slope parallel lineations are visible running up slope above the dense vegetation at the base; These lineations are aligned with regional bedrock foliation orientation and indicate that the slope is likely to be composed of schist bedrock (Figure 3.9C). Beneath the bedrock slopes areas of dense vegetation and light grey coloured material are visible(Figure 3.9D). The light grey material appears to be unconsolidated and is likely regolith that has been exposed by landsliding.

The northern side of Robinson Creek is dominated by bedrock slopes while the southern side is largely obscured by vegetation. Persistent parallel lineations on the slope to the north of the creek extend from creek level to the top of the slope (Figure 3.9E). These lineations extend from the western extent of the zone down to near highway level, however, it appears that near highway level the lineations are only visible near the tops of slope (Figure 3.9F). The lineations also align with regional bedrock foliation indicating that the slope is likely composed of bare bedrock. The lineations visible on the northern side of the creek are not present on the southern side; Instead a dense cover of vegetation completely obscures the ground surface. Only small areas of the slopes surface are visible where landsliding has exposed the underlying materials revealing light grey coloured unconsolidated material. The material is likely a cover of regolith and may cover the majority of the slope, but this cannot be confirmed with aerial photography.

The ability to identify the geomorphic units on slopes facing the highway is extremely limited due to the very dense vegetation cover over most of the slope. The presence of two large gullies can be observed as changes in the height of the tree canopy as a result of the changes in the underlying topography (Figure 3.9A). The material that is visible where vegetation has been removed by landsliding processes is grey in colour and appears to be composed of unconsolidated material. Based on the visible material it is likely that regolith is covering bedrock as it is not visible anywhere in this exposure. The presence of bedrock on the lower slopes can be inferred from the highly channelised nature of the creeks that flow in gorges before entering the Haast River. Direct observations of bedrock exposures are not visible in the aerial photo due to the dense vegetation cover.

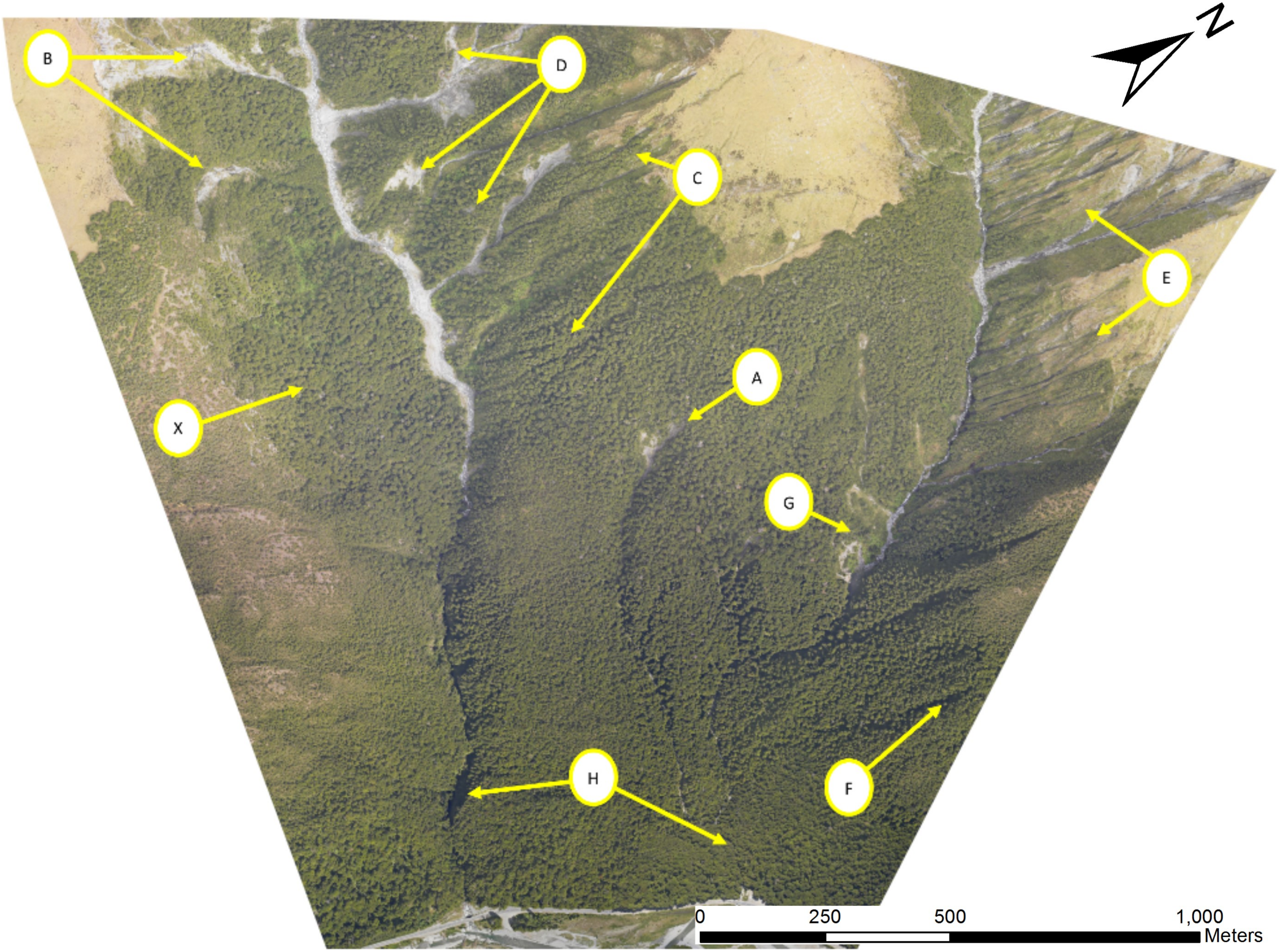

Figure 3.9: (A) Regolith material exposed in gulley due to mass movement (B) Areas where bare rock is exposed and likely where rockfall has taken place recently (C) Foliation aligned lineations exposed on upper slopes north of Wilson Creek (D) Exposure of regolith due to mass movement processes (E) Foliation aligned lineations exposed on upper slopes north of Robinson Creek (F) Subtle lineations visible in vegetation on upper slopes (G) Exposures of regolith cover caused by mass movements south of Robinson Creek (H) Creeks flowing in steep gorges before entering the Haast River.

3.4.2 LiDAR Surface Analysis

The slope facing the highway north of Wilson Creek and south of Robinson Creek is composed of a thin regolith veneer over bedrock. Bedrock textures visible in other parts of the zone are absent from this slope and instead two differing surface textures are visible (Figure 3.10 A and B). The textures on the upper slope appear more hummocky and irregular suggesting the material is likely to be regolith scoured from the failure of schist bedrock further up slope. An example of the processes of bedrock failure and deposition of regolith material on the slope is visible where a landslide has deposited regolith over the slope (Figure 3.10 C). The lower slope is also covered by regolith, however, the appearance differs from the irregular textures of the upper slopes. The surface is smooth and planar with many flat lying surfaces across the slope that aligning to form a planar but discontinuous surface (Figure 3.10 D). The presence of the steep sided gorges formed in bedrock to the north and south of the slope combined with the presence of isolated areas of bedrock on the lower slopes (Figure 3.10 E) indicates that the cover of regolith is relatively thin.

Large Regolith deposits below steep bedrock slopes in the upper reaches of Wilson Creek are clearly visible in the LiDAR model. On the south side of the creek large bedrock cliffs are visible at the top of the slope with planar surface textures on the cliff face formed by rockmass defects (Figure 3.10 G). Below the cliffs a very extensive and thick regolith deposit covers approximately half the slope from above the gorge to the western extent of the zone (Figure 3.10 H). Within the regolith deposit a number of internal scarps suggest that mass movements of the material, likely debris sliding, has or is taken place (Figure 3.10 I). The slope on the northern side of the creek is composed of bedrock with amounts of regolith covering eastern portion of the creek near the gorge entrance (Figure 3.10 J). At the western extent of the zone thicker deposit of regolith covers the lower part of the bedrock slope. Within the regolith material a number of landslide features are visible with headscarps and lateral scarps as well as main landslide bodies visible. The headscarp area of the landslide feature visible in the LiDAR model (Figure 3.10 K) also corresponds to an area of disturbed vegetation in the aerial photo, suggesting recent mass movements of the regolith deposit 3.9 D middle arrow).

The slopes above Robinson Creek consist of bare bedrock on the northern side and bedrock covered by variable thicknesses of regolith on the southern side. In the upper half of the creek the slopes on the northern side are entirely composed of bare bedrock with lineations parallel to bedrock foliation visible cutting across the slope (Figure 3.10 J upper arrow). On the southern side the upper half of the slopes above the creek consist of a thin cover of regolith over most of the slope with small areas of bedrock exposed in cliffs near the base of the slope. In the lower half of the creek the slopes become covered in thicker deposits of regolith with two distinctive regolith textures visible. The textures visible next to the channelised creek appear planar, smooth and flat lying and look similar in appearance to the lower slopes between Robinson and Wilson creeks (Figure 3.10 M). Above the planar smooth textured regolith a more irregular hummocky regolith texture is visible extending up slope (Figure 3.10 N). Parts of the irregular textured regolith appear to have been eroded and replaced by the planar, smooth flat lying regolith (Figure 3.10 O). Above the irregular textured regolith the slope displays structures consistent with bare bedrock and is inferred that this area is composed of bedrock (Figure 3.10 L).

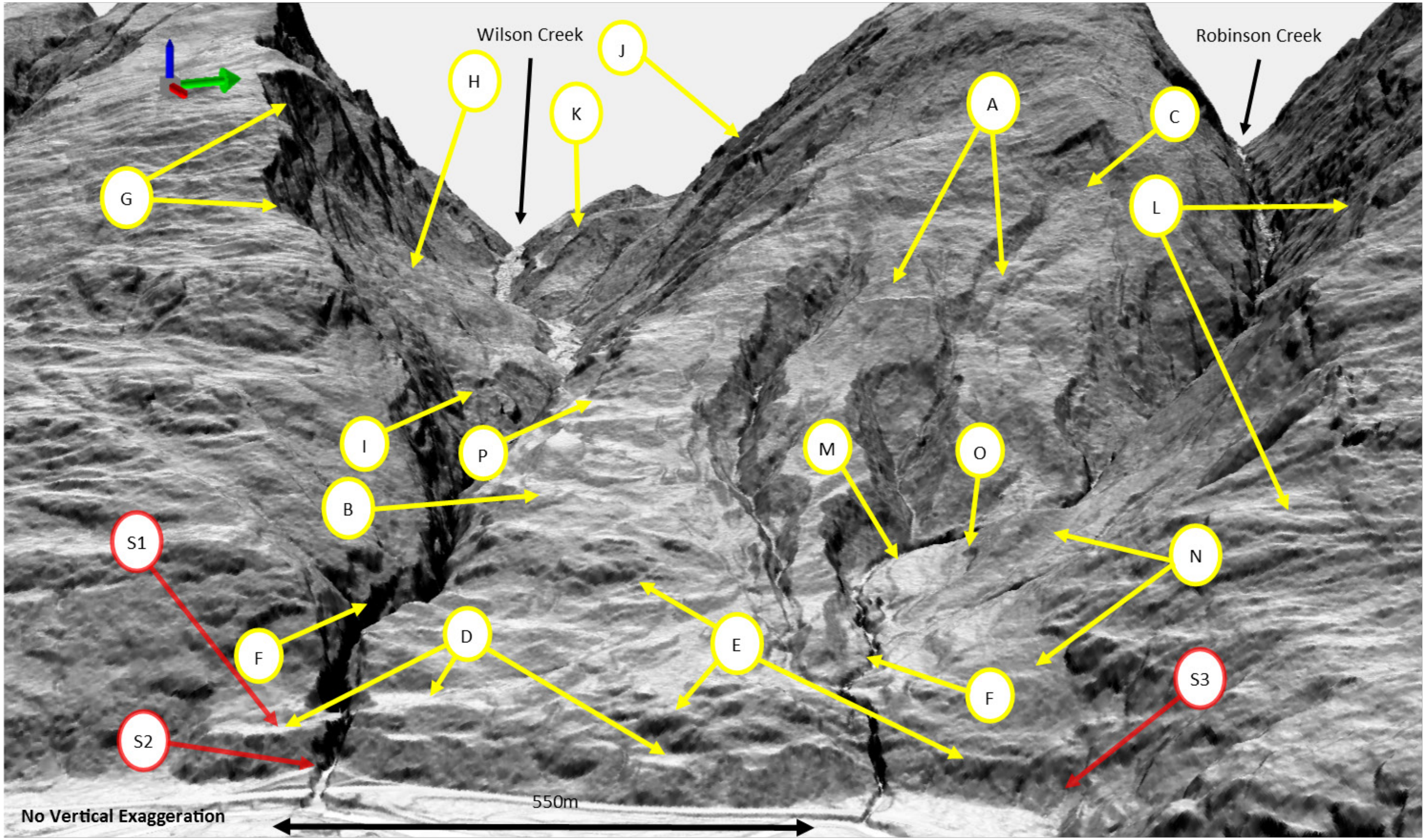

Figure 3.10: The background image is a slopeshade image with Light colours indicate shallowly sloping areas with steep areas appearing as dark colours. (A)Irregular and rough regolith textures on upper slopes (B)Planar smooth regolith textures over lower slopes (C)Deep regolith cover below landslide scarp (D)Flat planar surfaces at similar elevations (E)Small exposure of bedrock (F)Creeks flowing in steep gorges (G)Large cliffs on the southern side of Wilson Creek (H)Regolith deposit at the base steep cliffs (I)Scarps within regolith material indicating landslide activity (J)Bedrock slope with foliation aligned lineations visible (K)Regolith material at base of bedrock slope (L)Bedrock exposed on upper slopes with foliation lineations visible (M)Smooth planar regolith textures (N)Irregular rough regolith textures (O)Area where irregular rough textures appear to have been eroded. S1 and S2 refer to ground truthing sites one and two.

3.4.3 Ground Truthing

Site one is located just south of the Wilson Creek gorge outlet on the side of a flat planar discontinuous surface identified in the LiDAR model analysis (Figure 3.10 S1). The site consists of a small exposure where vegetation has been removed by a small landslide. The material exposed consists of rounded cobbles and boulders set in a finer matrix obscured by moss. The presence of rounded cobbles and boulders indicative of material that has been transported by fluvial processes and its location above the river suggests that the exposure is part of an alluvial deposit. The presence of alluvial material within the planar discontinuous surface suggests that the surface that extends up slope is the remnants of an old terrace, potentially deposited by the creeks before they incised into bedrock or could be an old terrace from the Haast River (Figure 3.10 D).

Figure 3.11: SITE One. Rounded clasts exposed on the side of a planar smooth surface identified in the LiDAR analysis. The material if inferred to be part of a river terrace with evidence that the terrace surface extends across lower parts of the slope (Figure 3.10 D).

Site two is located at the northern end of the zone on a steep slope just below a bedrock cliff approximately 90 metres from the highway (Figure 3.10 S3). The site consists of an exposure of regolith where vegetation has been removed by a small landslide (Figure 3.12). The material exposed consists of angular gravels, cobbles and small boulders set in a coarse sandy matrix. The clasts appear tabular as a result of breaking along the foliation defect within the schist rock the clasts are composed of. With the site situated below a steep cliff and the angular nature of the material the deposit is an exposure of colluvium.

Figure 3.12: SITE Two. Colluvium exposed on a steep slope next to the highway north of Robinson Creek (Figure 3.10 S3). The material exposed consists of angular coarse gravels, cobbles and small boulders set in a fine matrix of coarse sand (NZGS Classification). The material is likely a mix of regolith from the slopes above and fresh clasts of schist rock from the bedrock outcrops at the top of this small slope.

3.4.4 Geomorphological Interpretations

The majority of the slope facing the highway in this zone is covered by a thin sheet of regolith covering bedrock. Slopes adjacent to the highway consisting of regolith contain both colluvium and alluvium with isolated bedrock areas on the lower slopes; the alluvial material was likely deposited by the creeks prior to the incision of the creeks into gorges. The middle and upper parts of the slope are dominated by landslide derived colluvial material that appears in the LiDAR model as rough irregular textures that appear to cover some of the alluvial material at the interface between the colluvium and alluvium (Figure 3.10 P).

The creek valleys are characterised by steep bedrock cliffs and slopes with regolith deposits common at the base of slopes in Wilson Creek. The upper area of Wilson Creek is characterised by large bedrock cliffs on the southern side of the valley and a steep bedrock slope on the northern side. At the base of both slopes are large and thick deposits of regolith sourced from slope failures of the bedrock cliffs above. The lower reaches of the creek flow through a deep bedrock gorge before exiting next to the highway and into the Haast River. The upper area of Robinson Creek lacks the considerable thicknesses of regolith found in Wilson Creek with the southern slopes covered by a thin veneer of regolith with bedrock cliffs at the base of the slope and a slope entirely composed of bare bedrock on the northern side of the creek. In the lower reaches of Robinson Creek the creek bed is confined to a narrow gorge cut through what is inferred to be alluvial sediment and into the underlying bedrock.

Mass movement processes are confined to the steep slopes adjacent to the highway and the mid to upper slopes facing the highway. The slopes next to the highway have been subjected to debris slides recently as the presence of the exposures of material in Figures 3.11 and 3.12 indicates recent movements. The mid to upper slopes show signs of recent activity with small debris slides visible in aerial photographs within both gulleys and on the slopes bordering Robinson Creek. Mass movement processes do not appear to be acting on the alluvial material between the slopes adjacent to the highway and the colluvium covered upper slopes so this area is thought to be stable/inactive at the present time.

Mass movements processes in the creek valleys appear to be very active. Wilson Creek is the most active area with rockfall activity visible on the cliffs to the south and debris sliding of the bedrock slope on the northern side of the valley. The regolith material at the base of both slopes appears to be prone to debris sliding with a number of recent failures visible in the aerial photography and scarps visible in the LiDAR imagery. Mass movement processes in the upper areas of Robinson Creek consist of extensive rockfall debris sliding and rocksliding of material from the bedrock slope to the north with the southern slope showing signs of debris sliding of the thin colluvium cover.

3.4.5 Slope Hazard Identification

The geomorphological interpretations have shed light on the potential hazards that active slope processes may have on the highway. Relatively small debris slides are the most likely events to occur in this zone with the potential for much larger valley blocking landslides in the tributary valleys also a significant hazard. Other active slope processes such as rockfall and debris sliding in the creek valleys and on the upper slopes are not likely to have a direct impact on the highway. The hazards that may affect the highway directly or indirectly are summarised below:

1. **Debris Slides:** There is the potential for the regolith material on the steep slopes adjacent to the highway to generate debris slides. Debris slides of this material were observed in the second ground truthing site and are likely to be relatively small rainfall triggered events. The instability observed on the upper slopes appeared to consist of relatively small debris sliding events and given the distance from the highway it is unlikely to have an impact. The primary debris slide hazard the highway is exposed to is small events originating from the steep regolith covered slopes at the very bottom of the slope.

2. **Valley or Gorge Blocking Landslides:** The Wilson Creek valley showed the largest and most widespread instances of active slope processes in this zone with the large deposits of regolith at the base of the slopes showing signs of movement. There is the potential that if a large quantity of the regolith deposit was to fail it would form a landslide dam across the valley. This event would be particularly hazardous if it was to occur near the entrance to the narrow gorge where even a small outburst or failure of a landslide dam would result in a torrent of water being focused through the gorge and impacting the highway just 20 metres from the gorge exit. The probability of this event occurring is unknown but from analysis of aerial photography and LiDAR imagery it appears that the conditions exist for such an event to occur.

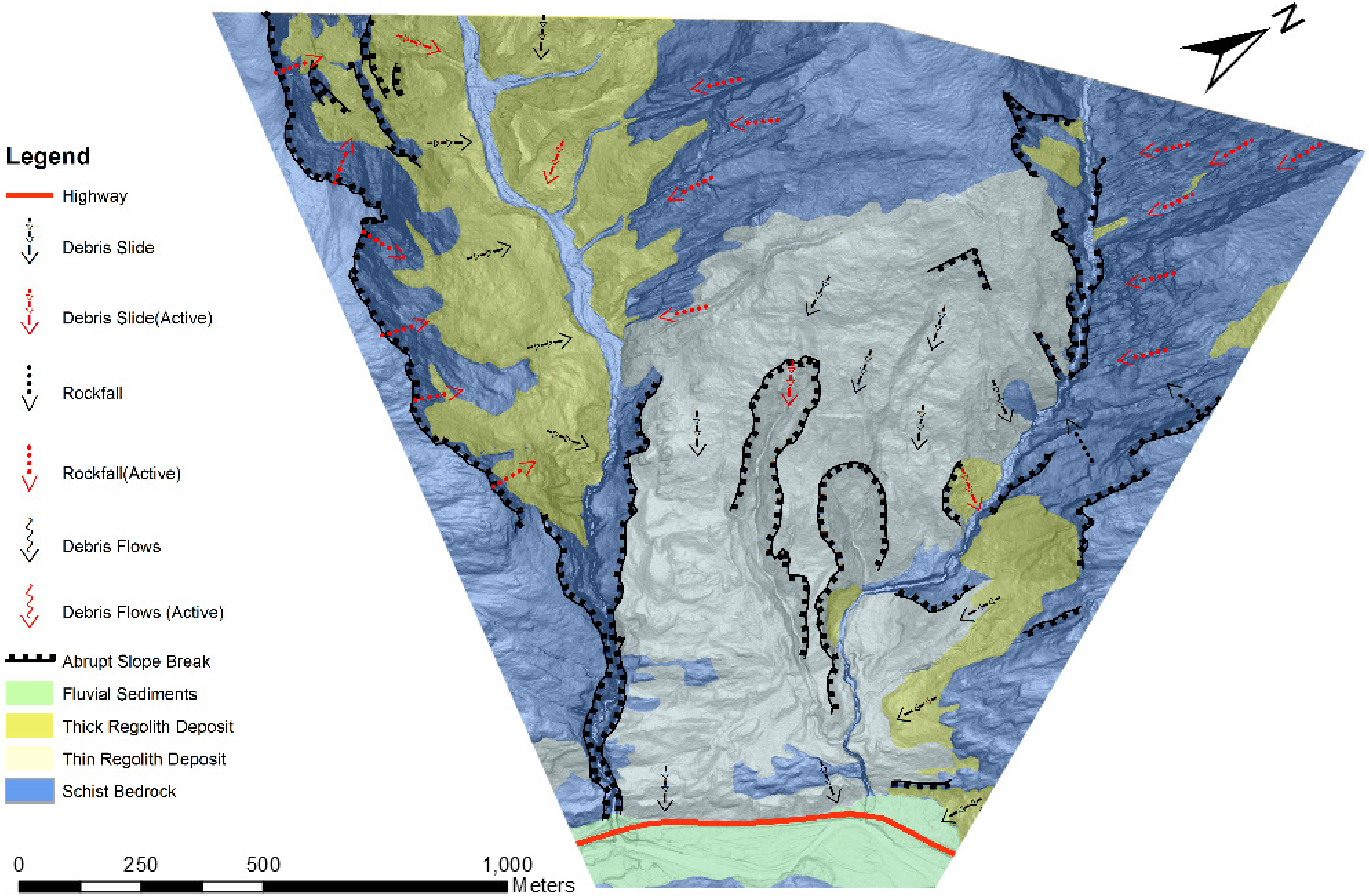

Figure 3.13: Geomorphology of the western hillslope above the highway between Wilson Creek and Robinson Creek. The background image is a slopeshade of the LiDAR model.

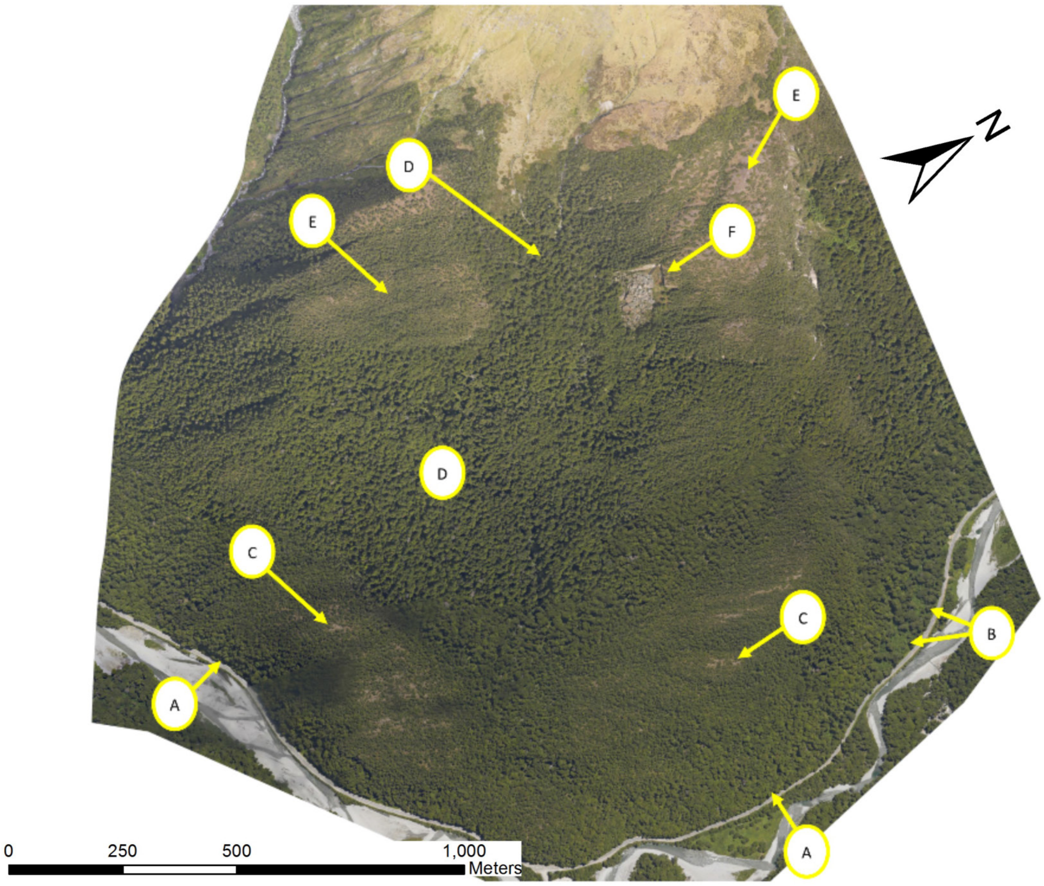

Figure 3.14: (A) Areas of dense vegetation next to the highway (B) Areas where younger vegetation is present and appears lighter in colour than surrounding vegetation. (C) Sparsely vegetated areas appearing light brown in colour surrounded by denser vegetation. (D) Very dense vegetation extending across the mid slope and in a narrow area to the top of the slope. (E) Areas of Sparse vegetation with subtle foliation aligned lineations visible on the southern side of the slope.(F) A landslide originating in the sparsely vegetated area on the northern side of the slope. The scarp and the landslide deposit are visible and appear to be associated with a rock/debris slide.

3.5 Robinson Creek to Pipson Creek

3.5.1 Aerial Photo Analysis

Vegetation cover in this part of the Haast Pass is highly variable with some are covered by dense vegetation and others with sparse or no vegetation at all. The areas adjacent to the highway are covered by very dense vegetation that completely obscures the ground surface (Figure 3.14 A); there does not appear to be any recent slope failures in this area and only two areas of slightly younger vegetation suggests past slope failures have occurred in the past(Figure 3.14B). Above the slopes next to the highway the vegetation variability becomes more pronounced. Areas of sparse to no vegetation appear light brown in colour and are surrounded by vegetation less dense than areas next to the highway (Figure 3.14 C). An area of particularity dense vegetation extends across the the middle of the slope and extends up to the top of the slope confined to a narrow area (Figure 3.14 D). Either side of the narrow area of dense vegetation the slope is sparsely vegetated with the southern side appearing to also show sighs of foliation aligned lineations (Figure 3.9 E). The only clear evidence of a mass movement visible in aerial photography is a small landslide with a well defined headscarp on the northern side of the upper slope where a rockslide has originated from an area of sparse vegetation (Figure 3.14 F).

3.5.2 LiDAR Surface Interpretation

The areas adjacent to the highway are composed of a combination of steep bedrock cliffs and regolith deposits. The bedrock cliffs appear as the dark surfaces next to the highway in the LiDAR model and consist of 30 to 40 metre high vertical faces above the highway and five to ten meter high faces next to the highway where the road has been cut into the rock (Figure 3.15 A). Below these cliffs the surface textures appear rough and undulating with slope angles of between twenty five and forty degrees. This rough and undulating surface represents regolith deposits likely sourced from the cliffs above (Figure 3.15 B). The highway in this area either crosses the base of these regolith deposits or is located beneath bedrock cliffs next to the highway.

Above the cliffs next to the highway the slopes are largely composed of bedrock with a large deposit of regolith in the middle of the slope. Bedrock structures are visible across most of the lower slope appearing as sets of ridges aligned with foliation. These parallel ridges extend up the southern and northern sides of the slope and indicate the presence of bedrock at the surface in these areas (Figure 3.15 C). The bedrock textures visible at the bottom and sides of the slope are obscured in the centre of the slope where an irregular and rough surface texture is visible. Part of the irregular and rough surface has been eroded by the creek near the bedrock boundary (Figure 3.15 F); the irregular undulating surface extends up slope confined to an area between higher bedrock areas to the north and south. The irregular and undulating textures represents regolith deposited after a large landslide. The source this landslide appears to be the large planar surface at the top of the slope where half of the material would have gone into Robinson Creek and the remainder has been deposited on this slope (Figure 3.15 A).

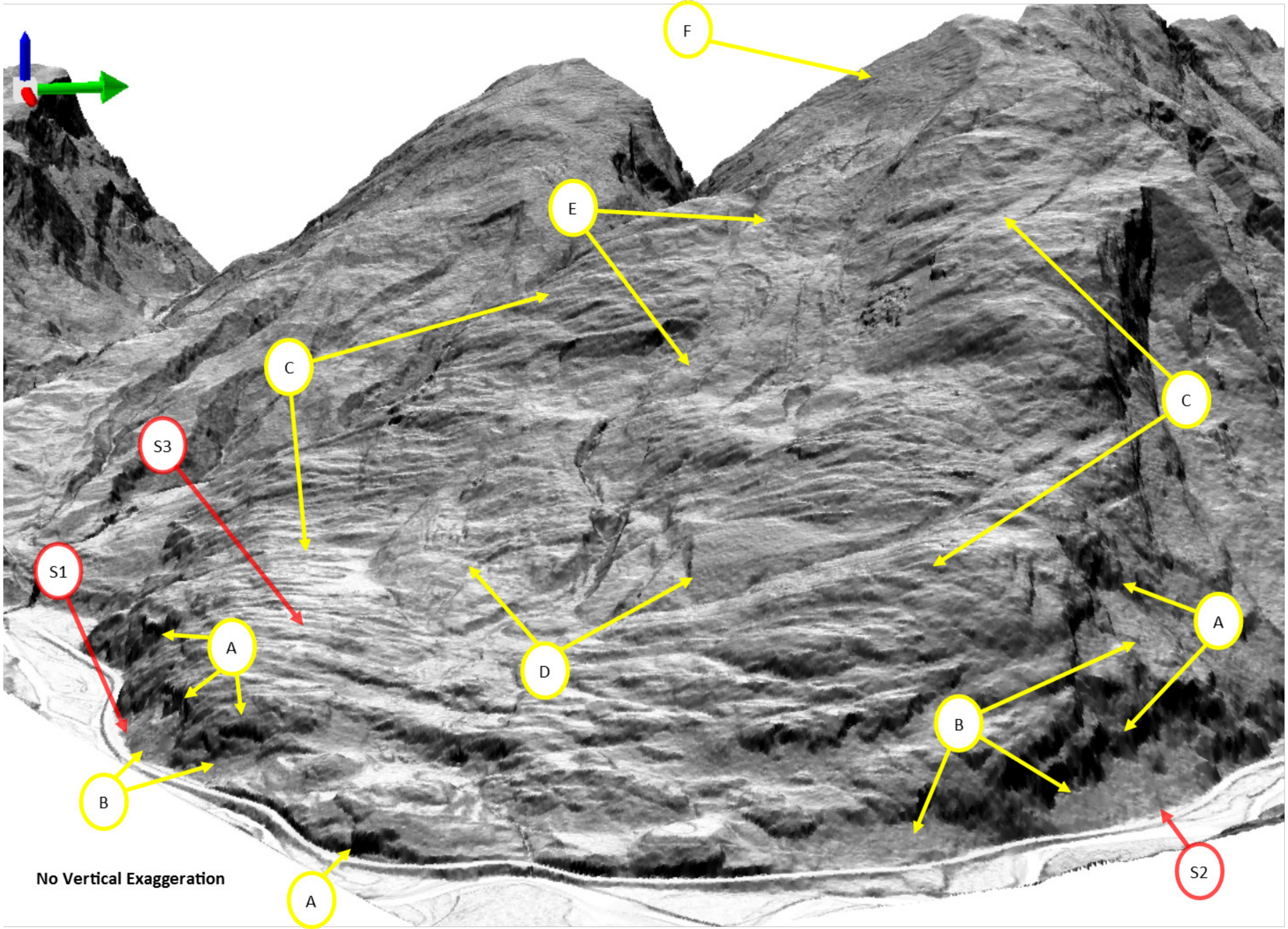

Figure 3.15: Slopeshade image of the LiDAR model. Light colours indicate shallowly sloping areas with steep areas appearing as dark colours. (A) Bedrock cliffs (B) Regolith deposits at the base of bedrock cliffs (C) Schist bedrock textures on lower slopes and either side of regolith covered area on upper slopes (D) Deposits of regolith over bedrock at the base of the upper slope (E) Narrow regolith deposit between two areas of bedrock with internal scarps visible (F) The upper area of the slope consists of a smooth planar surface and is likely the scarp formed by a landslide from this slope.

3.5.3 Ground Investigations

Ground truthing Site One for this area is located at the base of what was interpreted to be a regolith covered slope in the south of the area (Figure 3.15 S1). The material exposed consists of clasts up to one metre across set in a finer matrix that appears orange in colour. The clasts are composed of schist rock that are very angular with a platey shape as a result of the foliation in the schist. The matrix material consists mostly of angular gravels of schist rock with very minor amounts coarse sand and is non cohesive (NZGS Classification). The presence of this material at the base of the slope confirms the LiDAR interpretation that this area is a regolith deposit and can be further classified as a deposit of colluvium.

Figure 3.16: Site One. Exposure of material at the base of a large regolith deposit. The materials exposed consist of schist rock that are very angular and platey in shape as a result of the foliation in the schist. The matrix material consists mostly of angular gravels of schist rock with very minor amounts coarse sand and is non cohesive (NZGS Classification)

The second ground truthing site is located below cliffs in the north of this zone on a surface interpreted from the LiDAR surface analysis to be a deposit of regolith (Figure 3.15 S2). Figure 3.17 shows a view of the site looking up the slope in an area where a recent landslide has removed the vegetation. The deposit consists of large boulders, cobbles and gravels with a fine matrix present. The clasts consist of schist rock and are highly angular in appearance with most clasts consisting of coarse gravels and cobbles. The matrix material is light brown to orange in colour and consists of angular fine gravel and coarse sand that is non cohesive (NZGS Classification). In the vegetated areas either side of the exposure large boulders of schist are present measuring up to six metres across but the finer matrix material is obscured by the vegetation. The observations made confirm the interpretation made in the LiDAR model analysis that the slope is composed of regolith an can be further classified as a deposit of colluvium.

Figure 3.17: Site Two. Exposure of material on a regolith slope looking up slope towards large cliffs that are not visible in the image. The material exposed consists of large boulders, cobbles and coarse gravels that appear angular in appearance with a matrix consisting of fine gravel and coarse sand that is non cohesive (NZGS Classification).

The final area that was investigated on the ground is situated on the top of one of the parallel ridges identified in the LiDAR Surface analysis (Figure 3.15 S3). The area was interpreted to be composed of schist bedrock, based on the LiDAR model morphology, but the material was unable to be identified from aerial imagery. Site S3, shown in Figure 3.18, is situated in one of the less vegetated areas identified in the aerial photography as a light brown area. The light brown colour observed in the aerial imagery is a result of the moss cover over the bedrock that is visible in the photograph of the site (Figure 3.16 A). The dark area in Figure 3.18A just above the backpack is an exposure of schist rock where moss cover is absent. A close up of the exposure is shown in Figure 3.18B showing a prominent lineation within the rock. This lineation is foliation and measurements of its orientation matched that of schist bedrock in the area. The similarity of the foliation structures observed in this rock with that of schist bedrock indicates that the exposure is composed of schist bedrock and supports the interpretation that the ridges observed in LiDAR represent a schist bedrock surface.

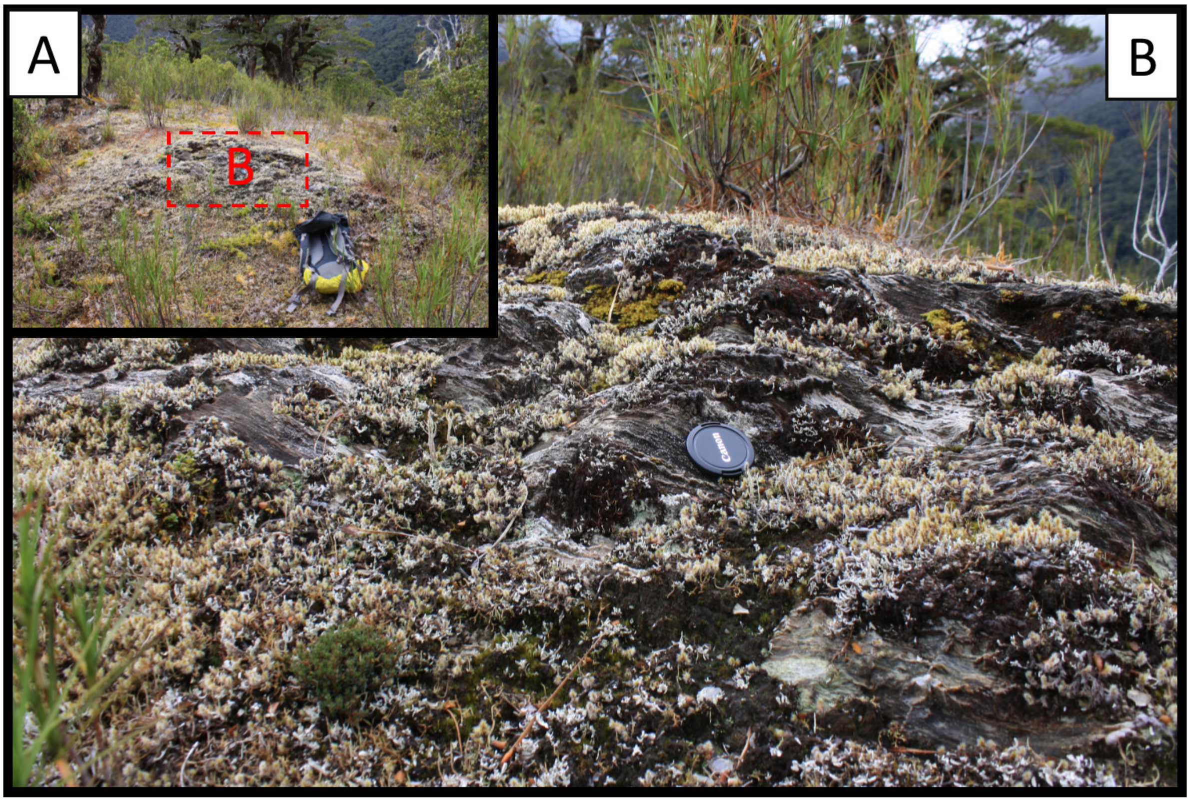

Figure 3.18: Site Three. (A) Area of sparse vegetation identified in the aerial photography as an area light brown in colour. The light brown colour is a result of the lack of vegetation and the moss covering this are. The dark are highlighted by the red dashed area is the location of the image in part B. (B) Schist foliation structures are visible as the subtle white lineations running across the image. Measurements of these structures reveal that the orientation matches that of bedrock indicating the exposure is in-situ bedrock.

3.5.4 Geomorphological Interpretations

Between Robinson and Pipson creeks the slopes next to and above the highway largely consist of bedrock with some large deposits of regolith. Next to the highway large bedrock cliffs are present both alongside the highway and hidden in the vegetation further up slope. Below many of these cliffs large deposits of regolith are present as a result of rockfall from the cliffs above. The cliffs next to the highway are shown as the abrupt slope breaks in Figure 3.19 with the large and deep deposits of regolith shown as the yellow shaded areas. Above the steep slopes next to the highway the slopes are mostly composed of bedrock with a large regolith deposit in the centre of the slope. This regolith material covers a large area of the mid slope but is confined to a narrow area in the upper slope flanked by bedrock areas. The regolith material on the upper parts of this slope was likely deposited by a failure originating from the landslide scar at the top of the slope. Debris sliding of the material has likely resulted in the movement of the material further down slope and the presence of scarps may indicate ongoing deep seated sliding of the regolith.

Mass movement processes are active on slopes next to the highway and on upper slopes. Evidence of recent debris sliding of the regolith deposits below the cliffs adjacent to the highway was identified in the ground truthing investigation at site S2 (See Figure 3.17). It should be noted however that the failure identified in the ground investigation is not visible in the aerial photography of the area and is largely obscured from highway by a very dense tree canopy and undergrowth. Rockfall from the steep cliffs above these regolith deposits is likely to be the source of the material however it was not possible to evaluate the condition or stability of the cliffs in this study. The flat bedrock surfaces above the cliffs next to the highway are not subjected to mass movement processes as the surface is composed of exposed bedrock with little to no regolith cover. The upper slopes, however, do appear to be subjected to rockfall from the schist bedrock either side of the regolith deposit.

3.5.5 Slope Hazard Identification

The main hazards that the highway is exposed ot within this zone are from debris slides originating in the regolith deposits next to the highway as well as rockfall from the cliffs adjacent to the highway and those high above beyond the regolith deposits. A summary of these potential slope hazards is provided below:

1. **Debris Slides:** Throughout the area numerous thick regolith deposits were identified next to the highway with a large portion of the highway situated between the river and the base of the deposits. Ground investigations revealed that debris sliding events were taking place, but were difficult to identify from aerial photography. Given the large area covered by the regolith deposits and the proximity of the highway to the base of the deposits presents it is likely that further debris slides will occur in the future and if they do occur are likely to have a direct impact on the highway.

2. **Rockfall:** In many parts of the lower slope steep bedrock cliffs are present next to the highway and above all the regolith deposits. The rockmasses at highway level appear to be relatively stable with the exception of a few areas where small blocks appear to be displaced at the tops of some of the cliffs. The cliffs above the regolith deposits are much taller and rockfall events have resulted in the build up of the regolith deposits. While it was not possible

to reach the cliffs during this study they pose a potential hazard to the highway as they have been active in the past and may continue to produce rockfalls of significant size in the future.

3.6 Synthesis

The aim of this chapter was to identify the surface units, slope processes and potential landslide hazards on the slopes above the highway in the southern zone. LiDAR has revealed that the slopes above the highway, between the summit of the Haast Pass and Pipson Creek, are predominantly composed of schist bedrock with minor deposits of regolith next to the highway and more substantial deposits located in tributary valleys. Most slopes above the highway appear to be inactive and are covered be dense mature vegetation. Active slope processes are largely confined to tributary valleys with some small cases of instability identified originating from the steeper slopes next to the highway, identified during ground truthing, but not visible from the air. Slope hazards potentially affecting the highway consist of debris sliding and rockfall from the regolith deposits and cliffs next to the highway with potential for debris flows at Wilson Creek caused by instability of large regolith deposits above the gorge. The impact and management options to address the slope hazards outlined are addressed in Chapter 6.

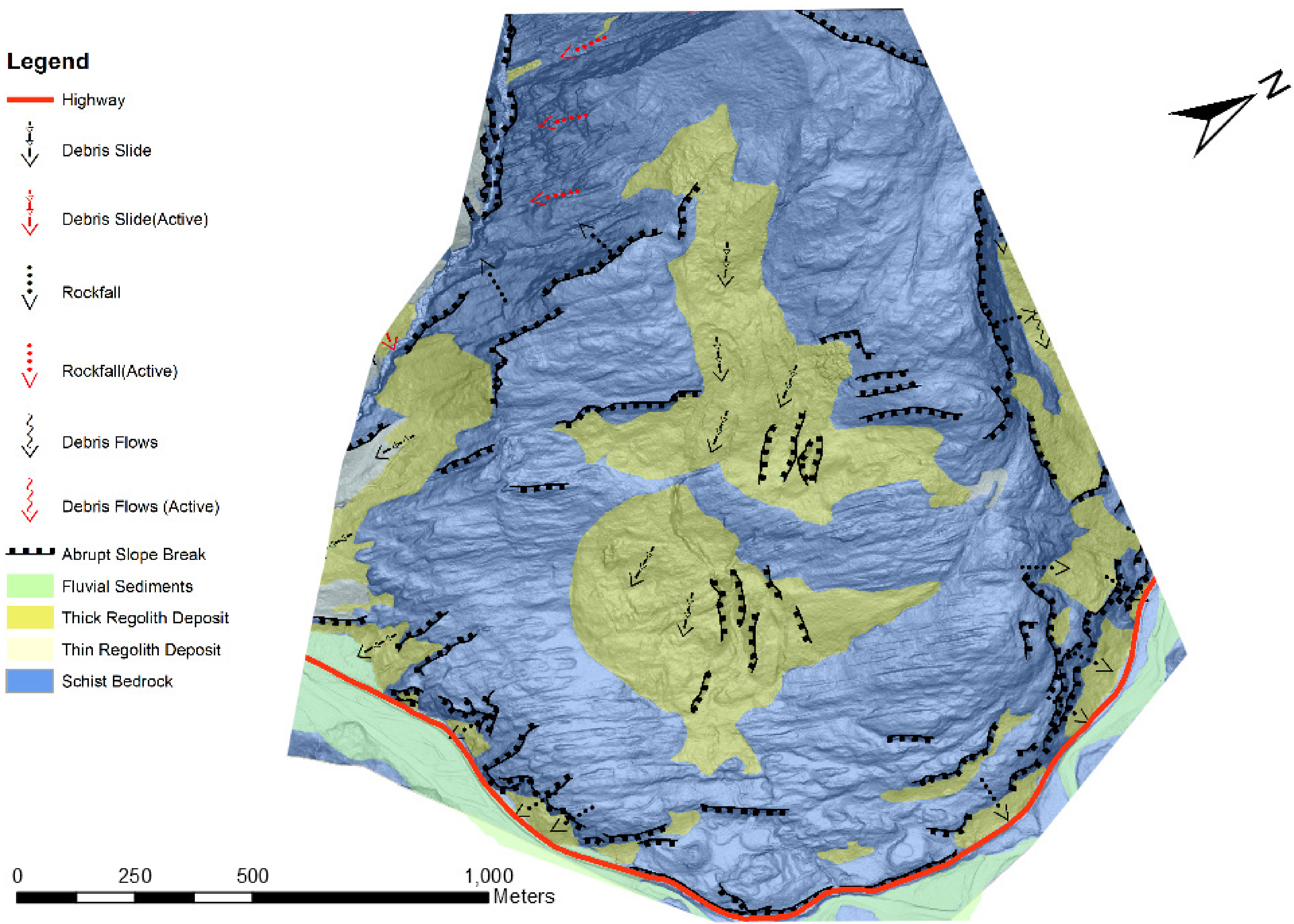

Figure 3.19: Geomorphology map of the western hillslope above the highway between Robinson Creek and Pipson Creek. The background image is a slopeshade of the LiDAR model.

Chapter 4

Northern Zone Geomorphological Analysis and Slope Hazard Identification

4.1 Introduction

Chapter four provides and analysis of the slopes above the highway in the Northern Zone defined as the area between the Pipson Creek Fans and the Thunder Creek Falls Car park. The chapter outlines the identification of surface units and both active or inactive slope on the slopes above the highway. Based on an understanding of surface units and slope processes it is then possible to identify the potential landslides hazards the highway is exposed to. In order to identify the surface units and slope processes a combination of aerial photo analysis, LiDAR model analysis and targeted ground investigation is used to generate a geomorphic map of the hillslope geomorphology above the highway. The map is then used as the basis for the assessment of potential slope hazards that the highway is exposed to and prioritisation of the sites to be investigated in the more detailed engineering geomorphology investigations in chapter 5.

4.2 Sub-Zone Segmentation

The Northern zone has been divided into two sub-zones based on a combination of surface units and processes observed on the slopes. The two zones consists of the slopes between the Pipson Creek Fans and the Hinge, and the slopes between The Hinge and the Thunder Creek Falls car park. The boundaries of the two zones are shown in Figure 4.1 as the solid red lines with the area within defined as the sub-zone. Figure 4.1 also shows the location of a number of creeks and place names referred to in the text to help locate the section of the slope that is being discussed.

4.3 Pipson Creek Fans to The Hinge

4.3.1 Aerial Photo Analysis

Identification of the surface units from aerial photography is very difficult as dense vegetation blocks observations of the ground surface in nearly all areas, the exception being the very top of the slopes above the tree line where vegetation is absent (See light brown area in Figure 4.2). Above the tree line the slopes appear to be largely composed of bedrock, with exposures visible as outcrops on

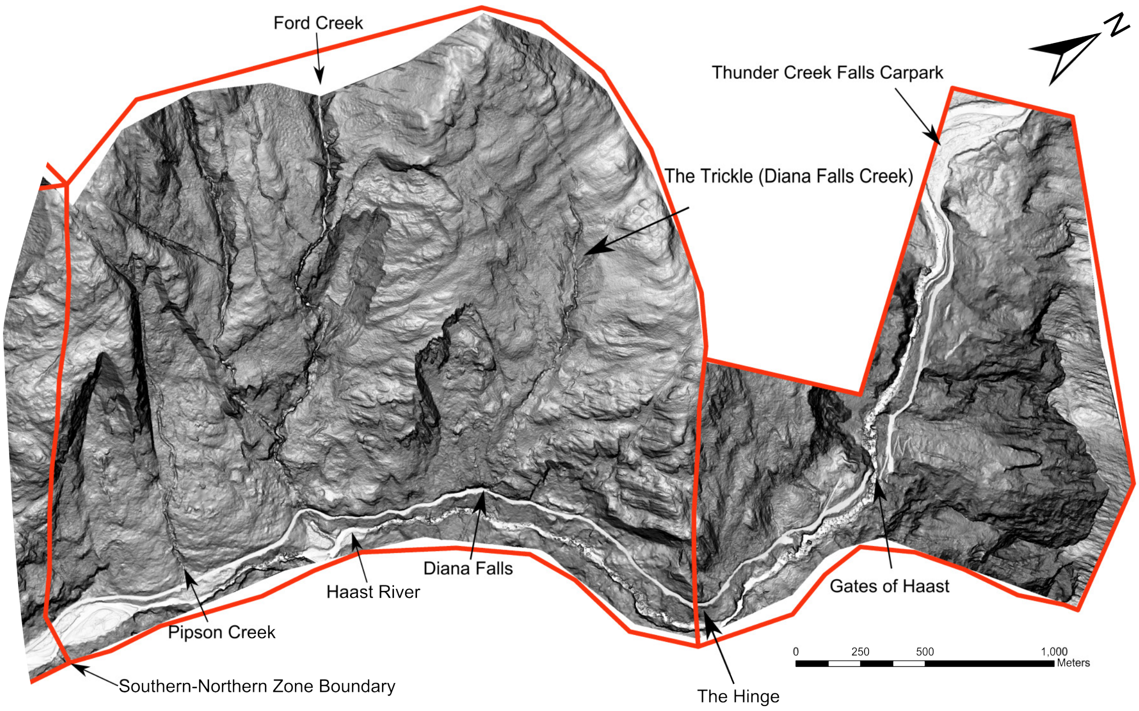

Figure 4.1: DTM of the Northern Zone with the sub-zones shown by the areas within the boundaries of the solid red lines. The locations of named watercourses and features are indicated and referred to throughout the geomorphic and hazard analysis to indicate location.

the sides of creeks (Figure 4.2 A) and in isolated areas as small bedrock cliffs or bare rock surfaces (Figure 4.2 B). The most significant feature on the upper slopes is the large cliff visible just above the tree line in the centre of the air photo (Figure 4.2 C); the cliff is an isolated feature with no others of a similar size visible in the upper areas of the slope. In isolated areas below the tree line patches of vegetation have been removed and identification of the surface units is possible; The surface units have been exposed following mass movements with unconsolidated debris visible above Ford Creek (Figure 4.2 D) and at Diana Falls (Figure 4.2 E). Outside of these areas it is not possible to identify the surface materials due to dense vegetation cover.

Evidence of recent mass movements are visible in the areas around Pipson Creek. The path of a recent debris flow is visible extending from highway level to the top of the slope where vegetation is absent and a light grey narrow track of remaining material is visible extending down slope (Figure 4.2 F). For most of the length of the debris flow the material has remained confined to the narrow channel of Pipson Creek, however, in one location it appears that material overtopped the channel and flowed alongside the main channel through vegetated areas on the north side of the creek (Figure 4.2 G).The debris flow appears to have originated at the top of the slope where Pipson Creek makes an abrupt bend to the south with the slope above appearing light grey to white in colour (Figure 4.2 H). The light grey colour of the surface compared with the surrounding hillside strongly suggests that a recent landslide has taken place. Since the area is thought to consist of bedrock the mass movement is likely to have been a rock slide or debris slide; it is possible that landslide could have acted as the trigger for the debris flow visible in Pipson Creek, however, without an exact date on when the failure occurred it is not possible to say with certainty.

The 2013 slope failure at Diana Falls is clearly visible in the bottom centre of the aerial photo of

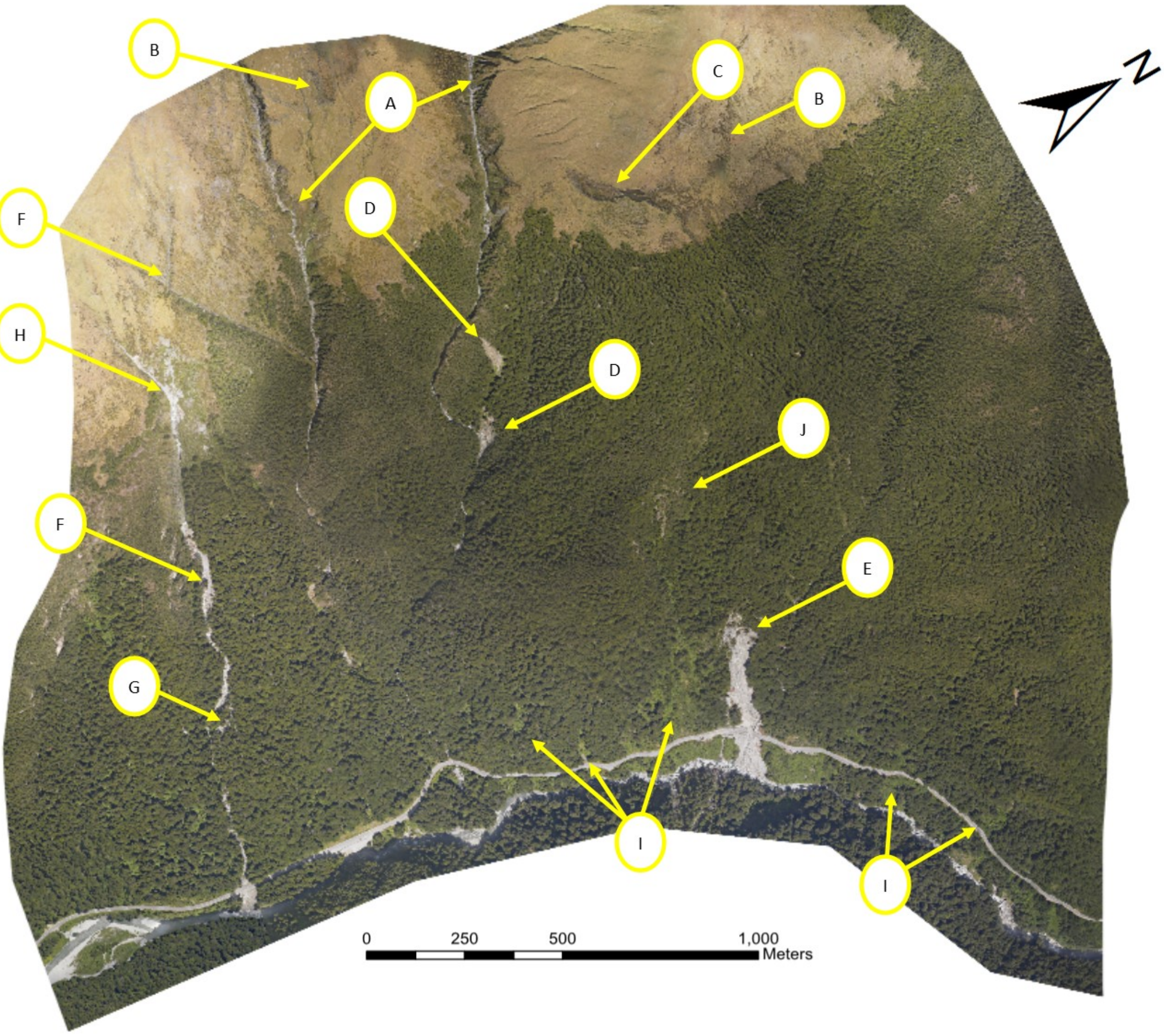

Figure 4.2: (A)Foliation aligned lineations visible in the sides of creek channels. (B)Bedrock visible as dark areas on light coloured slope with lineations visible. (C)Large cliff of schist rock that may be the headscarp of a larger landslide. (D)Landslide activity has revealed the underlying material that appears to consist of unconsolidated regolith material. (E)Clearly visible regolith material within the Diana Falls landslide area. (F)Light grey material visible running down slope indicates the path of the Pipson Creek Debris flow. (G)Fresh regolith material visible through the vegetation indicates the debris flow moved out of the channel. (H)Area of instability at the top of the slope. (I)Areas where variable aged vegetation indicates previous landslide events. (J)Rockfall visible from a steep section of slope far above the recent Diana Falls landslide.

the zone in Figure 4.2. It is the largest continuous exposures of regolith material on the slope and is clearly visible as the light grey area above to the highway (Figure 4.2 E). The material visible in the aerial photo consists of regolith with some large boulders visible within the regolith material, but most concentrated near the headscarp. To the north and south of Diana Falls a number of small areas of slope are covered by younger vegetation suggesting that recent landslides are not just confined just to Diana Falls but have likely occurred in additional locations alongside the highway(Figure 4.2 I). One of the more intriguing features visible in the area around Diana Falls is the presence of a small rockfall further up slope suggesting that a much larger portion of the slope outside of the 2013 Diana Falls landslide could be unstable (Figure 4.2 J).

4.3.2 LiDAR Surface Analysis

Analysis of the upper slope south of Ford Creek indicates the slope is predominantly composed bedrock with small isolated areas of regolith cover. The LiDAR model of the upper slope changes considerably with some areas consisting of subtle parallel undulations (Figure 4.3 A) and other areas having a rougher irregular texture (Figure 4.3 B). Throughout the upper slope in areas of both parallel undulation and rough textures small vertical cliffs are present and visible a the dark areas in the LiDAR Surface (Figure 4.3 C). Ford Creek and two smaller unnamed creeks cut across the slope flowing in narrow steep sided channels with cliffs visible as the very dark areas in the LiDAR model. The parallel well defined undulations are indicative of bedrock structure influencing surface morphology where it is exposed at the surface, but areas where it is well defined are limited to small areas. On other sections of the slope where bedrock structure become more subtle it is clearly still present and visible in the very steep slopes and in the cliffs on the margins of the creek channels. In areas where the rough irregular texture is visible the slope is covered by regolith, however, the cover of regolith on this part of the slope is relativity thin due to subtle bedrock structures influencing the slopes morphology.

The mid and lower portions of the slope south of Ford Creek consist of two large regolith deposits with small areas of bedrock present above and on the margins. The LiDAR model surface on the mid and lower sections of the slope consists of an undulating and very rough surface covering the entire lower slope and extending either side of a bedrock ridge approximately a third of the way up the slope (Figure 4.3 D). Flanking these rough surfaces are steep cliffs between 150 to 200 metres high. Beyond these are regular undulating surface structures with smaller cliffs, extending to the boundary with the southern zone and Ford Creek (Figure 4.3 E). The majority of this slope displays very rough irregular textures that represent two large and relatively thick deposits of regolith. The cliffs and parallel undulating textures are indicative of bedrock surface morphology in areas where bedrock is exposed and can be seen flanking the sides of the regolith deposit for most of the slope. The highway in this part of the zone crosses the base of the regolith deposits where there appears to be no sign of bedrock until the cliffs next to the highway, where Ford Creek (also known as The Trickle) crosses the highway.

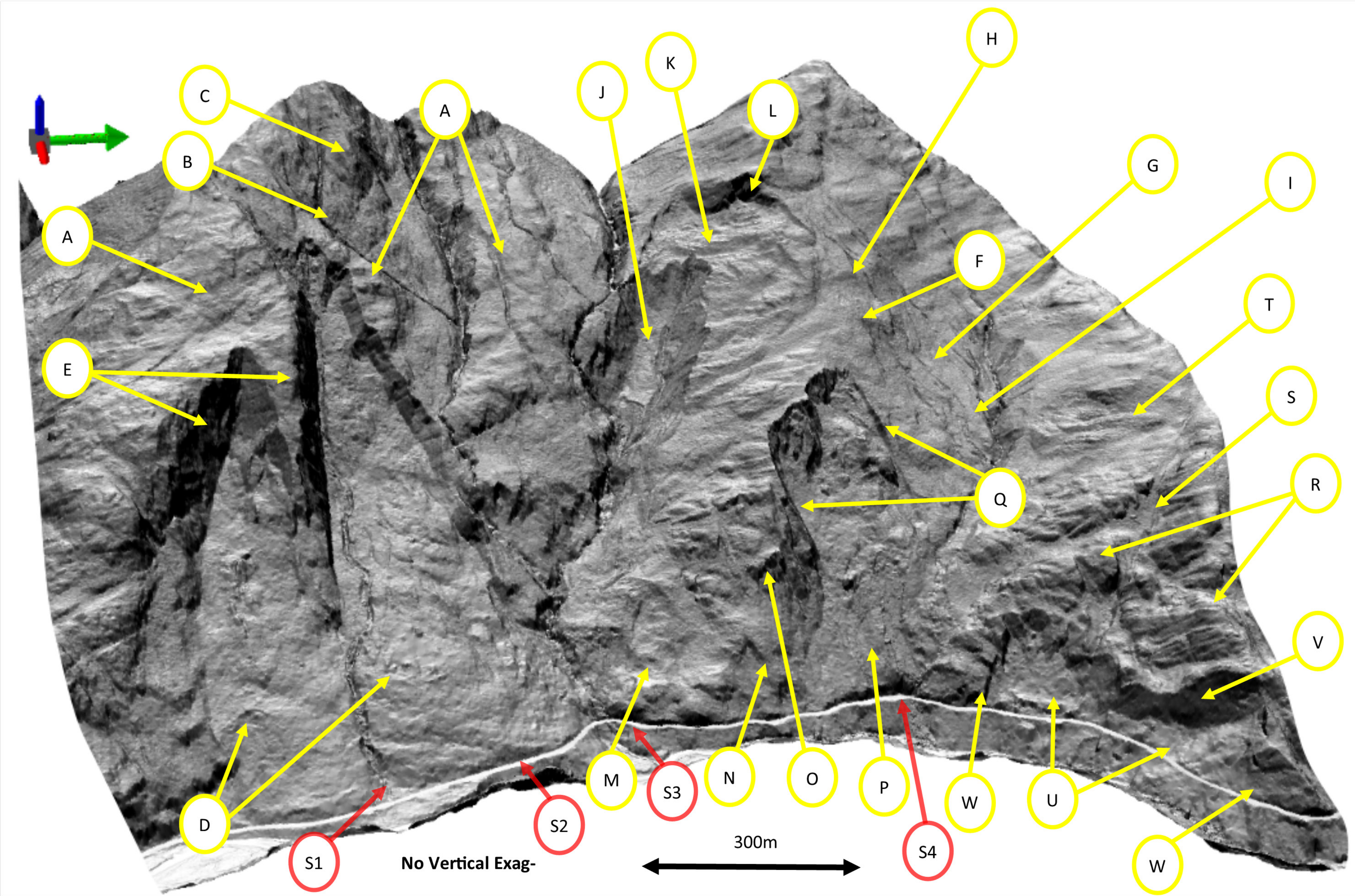

Figure 4.3: Figure caption on next page

Figure 4.3 Caption: LiDAR interpretation of the slopes between Pipson Creek and The Hinge.

A) Bedrock Morphology.

B) Regolith textures influenced by bedrock morphology.

C) Steep bedrock cliffs.

D) Very thick deposit of regolith with no bedrock textures anywhere within fans.

E) Steep bedrock cliffs above large regolith fans.

F) Bedrock morphology slightly masked by a thin cover of regolith.

G) Regolith textures completely obscure bedrock indicating a relatively thick cover.

H) Streams formed in narrow steep sided channels, likely flowing over bedrock.

I) Thick cover of regolith above the Diana Falls stream.

J) Depression within large landslide filled with regolith material.

K) Large area of slope with disturbed bedrock textures and a number of internal scarps.

L) Large headscarp above area of disturbed bedrock textures.

M) Regolith covered lower slope extending from Ford Creek across to Diana Falls.

N) Dark areas within regolith covered slope are bedrock cliffs.

O) Steep area of bedrock with surrounding area displaying typical bedrock morphology.

P) Extremely rough irregular regolith texture extending upslope to a prominent break in slope.

Q) Lateral scarps connected to a large headscarp at the top of a large regolith covered slope.

R) Bedrock morphology on the slopes above The Hinge with rockmass defects clearly visible as lineation's running across the slope.

S) Small deposit of regolith material below the steep slopes consisting of bedrock.

T) Deformation of the bedrock morphology in this are as well as a drop in slope and a potential headscarp above.

U) Thick deposits of regolith material at the base large steep cliff.

V) Steep bedrock cliff visible as the dark surface running across the slope above the large regolith deposit.

W) This area adjacent to the regolith is bedrock with subtle bedrock structures visible as well as a steep cliffs next to the highway at the edge of the zone.

The upper slopes between Ford Creek and Diana Falls consist of a combination of bedrock and regolith covered surfaces. The upper half of the slope predominantly consist of persistent parallel undulations, typical of bedrock surface morphology. The magnitude and visibility of these undulations change in some locations, sometimes becoming more subtle (Figure 4.3 F) and other times being completely absent (Figure 4.3 G). The widespread visibility of the parallel undulations indicates that most of the upper slope consists of bedrock at or very near the surface. In a number of locations on the upper slope regolith deposits obscure bedrock undulations. A deposit of regolith is present on the slope just to the south of Diana Falls with the upper area consisting of a thin cover (Figure 4.3 H), that becomes thicker near the middle of the slope next to the stream (Figure 4.3 I). Thicker regolith deposits are found on the slopes just to the north of Ford Creek with deposits at the bottom of a depression and on the slope below (Figure 4.3 J). The most significant surface feature is the disturbance of the upper slope to the north of Ford Creek (Figure 4.3 K). A large cliff is visible at the top of the disturbed mass with the boundaries visible as slope breaks, running across and down the slope (Figure 4.3 L). The slope depression partially filled with regolith is within the boundaries of the larger disturbed part of the slope and represents the surface expression of a very large slope failure. The overall slope disturbance is probably caused by slow creeping movement of the bedrock slope.

The lower half of the slope between Ford Creek and Diana Falls predominantly comprises regolith with some isolated patches of bedrock. A rough irregular surface is visible on the lower slope just to the north of Ford Creek (Figure 4.3 M), representative of a relatively thick deposit of regolith over bedrock. To the north of the regolith deposit the slope displays a rougher irregular surface morphology near the road (Figure 4.3 N) with a both steep cliffs and parallel undulations higher up (Figure 4.3 O). The irregular rough surface represents a cover of regolith, while the cliffs and parallel undulation above represent an area dominated by bare bedrock with thin patches of regolith scattered around. North of the bedrock dominated part of the slope (Figure 4.3 O), a very rough and irregular surface (Figure 4.3 P) is surrounded by steep abrupt breaks in slope on the southern and upslope sides, and a smaller break in slope on the northern side (Figure 4.3 Q). The very rough irregular surface is caused by the presence of a large deposit of regolith; given its roughness in the LiDAR model it is probably of a greater thickness compared to the regolith adjacent. The pronounced breaks in slope are probably scarps suggesting that the area has been subjected to a very large slope failure in the past with the regolith material representing the remains of the landslide.

The upper and mid slope between Diana Falls and The Hinge predominately consists of bedrock with a large regolith deposit at the base of the slope. The upper slope surface consists of two different surface morphologies: a smooth undulating surface with parallel undulations visible running across the slope (Figure 4.3 R), and a rougher irregular surface that is present at the base of many of the steep areas of the mid slope and is more extensive on the upper slope (Figure 4.3 S). The smooth undulating surface with parallel lineations indicates areas of bedrock at the surface with very little covering material. The rough surfaces found at the base of the bedrock areas in the mid slope are thin veneers of regolith that have been from failure of the bedrock cliffs above and weathering of the in-situ bedrock. The regolith cover on the upper slope is more extensive, but relatively thin given the exposure of isolated patches of bedrock and subtle undulations visible. There also appears to be some deformation of the bedrock lineations on the mid slope with a steeper part of the slope above that could be a headscarp to a deep-seated mass movement visible in Figure 4.3 T.

The lower portion of the slope between Diana Falls and The Hinge consists of a large bedrock cliff with a substantial regolith deposit at the base. Most of the lower slope has an irregular rough surface texture extending from river level up slope at an angle between 25 and 30 degrees (Figure 4.3 U). The irregular rough texture extends up to a steep cliff at an angle of between 65 and 70 degrees and varying in height between 40 and 80 metres (Figure 4.3 V). On the southern and northern sides of the rough irregular surface, the slope consists of smaller vertical cliffs and smother surface represent areas of bedrock (Figure 4.3 W). The rough irregular textures represent a large regolith deposit extending from river level to the large cliff and extends 700 metres across the base of the slope. The large cliff and the slope to the north and south of the regolith deposit formed in bedrock.

4.3.3 Ground Truthing

Ground investigations were undertaken at four sites between the Pipson Creek Fans and The Hinge to validate the interpretations made in the air photo and LiDAR analysis. The slopes in this part of the field area are very challenging and hazardous with vertical cliffs next to the highway making accessing the slope difficult. The Pipson Creek fans in particular, while accessible from the highway, were dangerous to travel across as large cavities between boulders were obscured by undergrowth and made identification of the cavities impossible; as a result investigations were focused on the relatively accessible Pipson Creek. Four sites were picked to be investigated: A site in Pipson Creek, an exposure of part of the Pipson Creek fan next to the highway 100 metres north of Pipson Creek, the cliff next to the highway near Ford Creek and the cliff at the base of Diana Falls.

The first ground investigation site is situated 30 metres from the road up Pipson Creek (Figure 4.3 S1). The location was the site of a debris flow in September 2013 and is at the base of the debris flow path identified in the aerial photography. The site was interpreted from the LiDAR model analysis to be composed of landslide debris and is situated in the middle of the two debris fans with their apex at the steep cliffs above. Figure 4.4 shows Pipson Creek looking up slope where large angular boulders of schist between two and six metres across are visible. Figure 4.5 shows a close up of the fine material that can be seen around and beneath many of the larger boulders and consists of smaller schist boulders, a range of gravel sized particles and coarse sand. The material visible in the creek is identical to deposits of debris flows on steep slopes and is situated within the channel of the observed debris flow path identified in aerial imagery. More large boulders similar in size to of the creek bed were present on the slope outside of the creek channel, but were not visible in the photography. Given the presence of the boulders outside of the creek channel it would appears that debris flows have affected other sections of the slope.

Figure 4.4: SITE 1a. View of the Pipson Creek channel looking upstream from a location 20 metres from the highway. Large angular schist boulders are visible in the main channel as well as in the banks. The finer material between the large boulders consists of smaller boulders up to one metre across, Cobbles and a range of gravel sized particles (NZGS Classification).

Figure 4.5: SITE 1b. This image is also taken at Site One and shows an exposure of the fine material found beneath boulders in the rest of the creek. The two areas of schist rock at the bottom of the image are part of large schist boulders with the material on top consisting of angular clasts of smaller boulders, cobbles and a range of gravel sized particles (NZGS Classification).

The second ground investigation site is situated next to the highway 100 metres north of Pipson Creek (Figure 4.3 S2). The site has been interpreted from LiDAR analysis to be part of a debris fan and is expected to be composed of schist debris similar to the materials observed in Pipson Creek. Ground investigations revealed that the surface of the slope is covered by schist regolith with some very large boulders in places. Figure 4.6 shows some of the larger boulders visible next to the highway and have foliation orientations varying from that of bedrock. Figure 4.7 shows an exposure of the debris fan material where the highway has been cut into the slope 50 metres above the river. The material that is visible consists of boulders up to two metres across with smaller ones less than one metre across scattered over the slope with a wide range of foliation orientations visible. There is a finer component to the material exposed on the slope obscured in the photograph in Figure 4.6 by thin vegetation and dark brown-white moss and lichen. Beneath the moss and lichen a mix of small boulders, cobbles and gravel is present with clasts ranging from angular to sub-rounded. The material observed at the site is supports the interpretation that this area is dominated schist debris.

Figure 4.6: SITE 2a. Photo of the Pipson Creek debris fan looking up slope from the highway 50 metres north of Pipson Creek. Three large schist boulders are visible. The first at the bottom of the image is approximately three metres wide and has horizontal foliation orientations. The second and third boulders are visible in the trees in the centre of the image surrounded by vegetation. Foliation orientations of these boulders are variable and do not match regional bedrock orientation indicating that they have moved in the past.

Figure 4.7: SITE 2b. Exposure of debris fan material 100 metres north of Pipson Creek where the highway has been cut into the slope 50 metres above the Haast River. The material consists of boulders, cobbles and gravel all angular in appearance with a wide range of foliation orientations (NZGS Classification). The road marker for scale and is one metre high.

Sites three and four consist of the cliffs next to the highway at Ford Creek (S3) and Diana Falls (S4). The cliffs were investigated to observe the features of the in-situ bedrock and to evaluate the stability of the rockmasses. To achieve this, rockmass defects and foliation attitude were measured and compared with the known regional bedrock foliation orientations. Figures 4.8 and 4.9 show two areas where the rockmass is well exposed with foliation orientation and defects clearly visible. The foliation orientations measured at the outcrops were approximately a 020 strike and a dip of 70 degrees with a variation of 10 degrees on strike and dip across measurements. Only one persistent defect was observed in the rockmasses north of Ford Creek and this defect was widely spaced varying from one to ten metres. The foliation measurements of the cliffs are not only similar to that of bedrock but are also remarkably consistent over distances of one to two kilometres. Initial observations suggest that many of the rockmasses appear to have unfavourably oriented defects, however, measurements of the rockmass revealed that there were only two persistent sets of defects; in order for failure to occur a third defect would have to interact to form a block that could slide out. Detailed measurements of foliation orientation were only able to be completed at two sites due to highway clearance issues, but the other rockmasses alongside the highway were observed to have similar foliation orientations when sighted from a distance.

Figure 4.8: SITE 3. Vertical cliff of schist rock next to the highway. Rockmass defects measured from this rockmass indicated only two persistent defects. The first persistent defect is schist foliation, visible as the face of the cliff, dipping between 70 and 80 degrees to the east and striking 000 to 010 degrees indicating that the schist cliff is an exposure of bedrock. The second defect consists of a joint set, visible as the lineations running across the cliff, dipping approximately 30 degrees to the east ad striking approximately 100 degrees. The person in the image is 175cm tall for scale.

Figure 4.9: SITE 4. Photo taken looking north towards the bottom of the Diana Falls landslide. The cliff next to the highway has foliation orientations matching that of schist bedrock and lacks many other defects with only one visible as the diagonal line running across the face. Note the darker material behind the orange crane that is a mix of vegetation and regolith that is typical of the material observed above many of the cliffs next to the highway.

4.3.4 Geomorphological Interpretations

The slope next to the highway between the Southern/Northern Zone boundary and Ford Creek consist of both thick regolith deposits and bedrock surfaces and cliffs. The lower part of the slope consists of thick deposits of regolith extending right across the lower portion of the slope to Ford Creek. There does not appear to be any exposures of bedrock in the lower part of the slope with the exception of small bedrock cliffs next to Ford Creek. In the middle of the slope the regolith deposit splits into two distinct fans and is flanked by steep bedrock cliffs on both sides. There is an area between Ford Creek and the regolith deposit on the mid slope that consists predominantly of bedrock with thin deposits of regolith present beneath steep bedrock slopes. The upper slope is almost entirely composed of bedrock with only thin deposits of regolith covering small areas.

The streams and creeks on the upper slope flow in deep, steep sided channels and a number of streams follow prominent rockmass defects resulting in abnormally straight channels. The most visible example is at the top of the northern debris fan where the stream flows straight down slope before heading north abruptly. The stream running straight down slope also aligns with the area of instability identified at the top of the northern most fan and is also aligned with the very tall bedrock cliffs on the southern side of the fan. Where the stream turns north it flows straight along another defect that is aligned with the sharp curves in Ford Creek to the north. The linearity and persistence of the straight sections of the creeks suggests that the rockmass defects that they are following are faults. The creek section oriented north-south are likely formed by faults that were exploiting the foliation weakness within the rockmass. The east-west striking linear creek above the apex of the northern Pipson Creek fan is also likely to be following a fault running perpendicular to foliation; evidence supporting the idea that it is a fault is the alignment of the creek with the unstable area at the apex of the Pipson Creek fan and the large bedrock cliff flanking the southern side of the northern fan.

The regolith deposits on the slopes between the Southern/Northern Zone boundary and Ford Creek are derived from a number of different mass movement processes. The large regolith deposits that cover the entire lower slope and most of the mid slope are a combination of two debris fans built up by multiple debris flows or debris slides. The source of the material for the mass movements appears to be the bedrock cliffs that surround the debris fan with recent rockfall and debris sliding visible in aerial imagery. The debris fan itself is subject to active mass movement processes with the debris flow event in September 2013, having started at the top of the fan and travelled down slope and across the road. The upper slopes appear to be largely stable with visible instability confined to the steep sided stream channels. The regolith material on the upper slope does not show indications of recent movements, with the vegetation covering the upper slope appearing largely undisturbed with a consistent density.

The slope above the highway between Ford Creek and Diana Falls is characterised by a combination of regolith and bedrock. The slope next to the highway largely consists of near vertical bedrock cliffs where the road has been cut into the slope. Above the bedrock cliffs next to the highway, regolith cover is variable on the lower and middle slopes and ranges from a thin cover to a very thick deposits of regolith. There are also some isolated patches of bare bedrock on the lower and middle slopes, but these are mostly confined to near vertical cliffs and one isolated area of predomi-

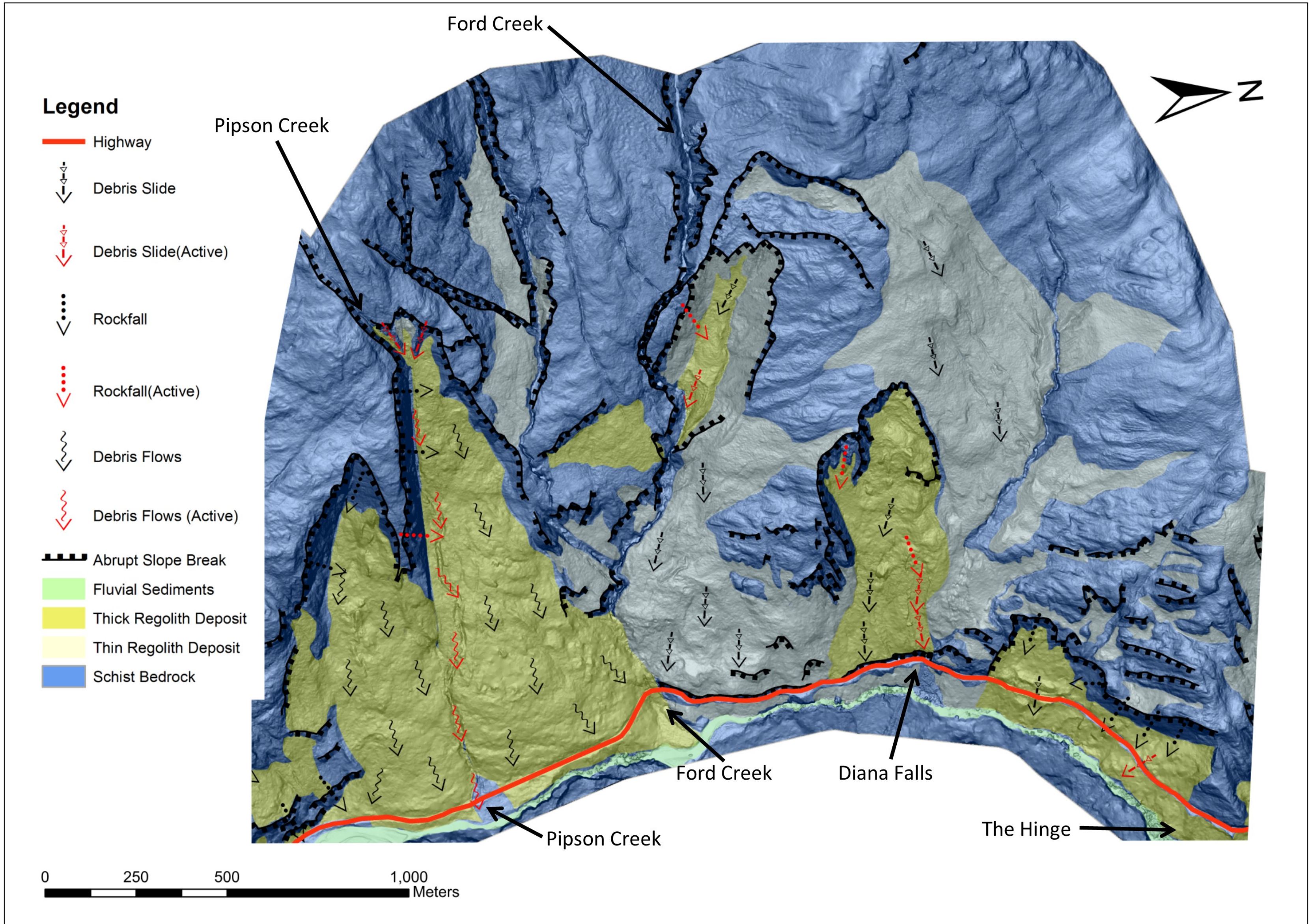

Figure 4.10: Geomorphology map of slopes above the highway between Pipson Creek and The Hinge.

nantly bedrock surfaces surrounded by regolith. The upper sections of the slope are predominantly composed of bedrock with only isolated areas covered by a veneer of regolith.

The regolith cover on the slopes above the highway originates from a number of different types of slope processes and source areas. The regolith cover on the lower slope next to Ford Creek has either been deposited by the large landslide visible indicated by the large area of bedrock structure deformation on the upper slope or has been deposited by successive debris flows action the slope before Ford Creek cut into the bedrock. The regolith on the slope appears to be unstable with evidence of recent slope processes visible as the bare areas in the aerial imagery. Further north the regolith beneath the bedrock area on the mid slope has likely been deposited by rockfall and debris sliding with material sourced from the bedrock area. The area does show signs of instability with areas of very young vegetation indicating recent slope failures. North of the bedrock area on the mid slope a large area of very rough surface textures interpreted to be regolith is surrounded by steep cliffs on two sides and a smaller cliff on the northern side. This regolith material appears to be the remnants of a very large landslide with the cliffs representing the headscarp and the lateral scarps. It is from within this regolith material that the Diana Falls landslide has originated and a significant amount of regolith material still remains on the slope. The thin regolith cover on the upper slope is sourced from debris sliding of material originating from the bedrock cliff above. Some part of the slope show signs of recent failures of this material, however, the failures are relatively small in both size and run-out distance with the overall slope appearing to be relatively stable.

Between Diana Falls and The Hinge the slopes above the highway are largely composed of schist bedrock with one large deposit of regolith. The lower portion of the slope consists of a large regolith deposit beneath a large bedrock cliff. To the north and south of the regolith deposit bedrock areas are present and visible as cliffs next to the highway and as bedrock textures in LiDAR. Above the bedrock cliff the slope is principally composed of schist bedrock with small areas of thin regolith deposits situated below some of the steeper bedrock areas. Towards the top of the slope the bedrock textures become more subtle indicting that a more extensive regolith deposit exists on the slope but its thickness is relativity thin.

There are a number of active and past slope processes acting on the slope that can be identified. The regolith deposit at the base of the slope has been built up by rockfall from the cliff; this talus has then become affected by debris sliding as a result of the river undercutting the toe of the slope triggering movement of the debris mass. Movement of this debris has been recorded previously in an engineering investigation in 2001 (Opus 2001) indicating these debris sliding processes were active at that time. On the upper slope the presence of regolith material below the steeper bedrock areas indicates that rockfall or debris sliding of the bedrock has occurred in the past. There is one area visible in the aerial photography where removal of vegetation from an area of regolith indicates that a debris slide of the regolith material has occurred and that these areas may be prone to active slope processes.

4.3.5 Slope Hazard Identification

The geomorphological interpretations highlight the potential hazards that the highway faces from slope processes. They include debris flows, debris slides, rockfall, and deep seated gravitational failures with almost the entire zone susceptible to one or more of these hazardous slope processes. A summary of the areas affected by each slope process as well as an evaluation of the likelihood of these processes affecting the highway is provided below:

1. **Debris Flows:** A significant debris flow hazard exists between the start of the Pipson Creek Fans and Ford Creek (The Trickle at road level). The two large regolith fans originating at the top of the slope have generated debris flows recently, and the area at the top of the slope where the September debris flow occurred, still appears unstable and is likely part of an old fault zone. While the recent debris flow appears to have remained in the Pipson Creek stream channel for most of the slope there is evidence in the aerial photography that sections of the debris flow left the channel and flowed across the slope.

2. **Debris Slides:** With regolith cover present just above the highway throughout the entire zone the potential for debris slides to occur presents a significant hazard to the highway. The material that presently covers the slope originates from rockfall from steep bedrock areas as well as the remnants of past debris slides. The material is likely to consist of unconsolidated schist boulders cobble and gravels that are not inherently stable with indirect evidence of previous failures indicated by variations in vegetation ages across the slope.

3. **Rockfall:** Large areas of the zone consist of bedrock cliffs and steep bedrock slopes so the potential rockfall hazards need to be understood. The cliffs next to the highway, investigated during ground truthing, revealed that the limited rockmass defects and their wide spacing meant that although areas appeared to have unfavourably orientated defects they were in fact relatively stable. In a number of locations on the slopes above the highway, evidence of recent rockfalls from cliffs were observed in some stream channels and particularly the headscarp of the larger Diana Falls landslide. This indicated that some sections of the bedrock slope are in a state of marginal stability and present a hazard to the highway.

4. **Highway Collapse:** In a number of locations in this zone the highway has been built across regolith deposits making these sections suceptable to highway collapse. The sections include where the highway has been built across the Pipson Creek Fans and across a large regolith deposit at The hinge. The potential for large sections of the highway to collapse in these areas is a significant potential hazard. Partial collapse of the highway is also a possibility in areas where the slope below the road is mantled with regolith and the highway itself is partially supported by this downslope material.

5. **Deep Seated Gravitational Failures:** Two potential deep seated gravitational landslides were identified in the geomorphological analysis of this zone. The first potential landslide is present on the slope above The Hinge, but with only some small rockmass deformations and a very subtle potential headscarp feature it is difficult to say with certainty if this is a landslide. The second deep seated landslide is present on the upper slope between Ford Creek (the Trickle at the road) and Diana Falls and covers approximately one square kilometre of the slope. The headscarp, lateral scarps and toe bulge are all clearly visible in the LiDAR

model with a large area of the landslide missing on the southern corner; this missing part of the slope may have failed resulted in the build up of most of the regolith visible across the lower slope. The state of activity of this landslide is unknown but presents a very large hazard to the highway with serious consequences if it were to fail.

4.4 The Hinge to Thunder Creek Falls

4.4.1 Aerial Photo Analysis

Aerial photo analysis of the slopes above the highway between The Hinge and the Gates of Haast Bridge shows clear indications of recent instability. Across most of the slope vegetation cover is very thick with mature trees visible in the aerial photo as the dark green coloured vegetation (Figure 4.11 A). While most of the slope is covered by mature dense vegetation there are areas where younger vegetation is visible. The young vegetation appears as the light green areas that are lower than the surrounding darker vegetation (Figure 4.11 B). This variability in vegetation maturity indicates that mass movement processes have likely been active in the recent past resulting in the removal of the more mature trees. An example of a recent landslide is visible as the light brown coloured area in Figure 4.11C where a debris or tree slide has removed vegetation. Based on the variations in vegetation maturity it appears that the slope above the southern approach to the bridge has been most active with larger areas of young vegetation compared with the slopes closer to the hinge (Figure 4.11 D). The dense vegetation on the slope made direct observations of the surface materials from aerial photography impossible with the exception of the slope below the bedrock cliff where regolith deposits are visible at the base of the cliffs and next to the river (Figure 4.11 E).

The slopes above the highway between the Gates of Haast Bridge and Thunder Creek Falls appears to be the most unstable part of the entire study area. It is possible to observe some of the surface units in small areas where vegetation has been removed. Bare schist rock is visible in a number of locations where landslides have removed vegetation and in stream channels (Figure 4.11 F) as are areas of regolith materials (Figure 4.11 G). The regolith material appears to consist of boulders of schist and unconsolidated finer material that appears to be fresh. The vegetation on the slopes above the highway is highly variable with a mix of mature vegetation and large areas of young vegetation (Figure 4.11 H). The younger vegetation is clearly visible in the aerial photo as the light green areas lacking mature vegetation with the large extent of the young vegetation indicating that large sections of the slopes have been recently active.

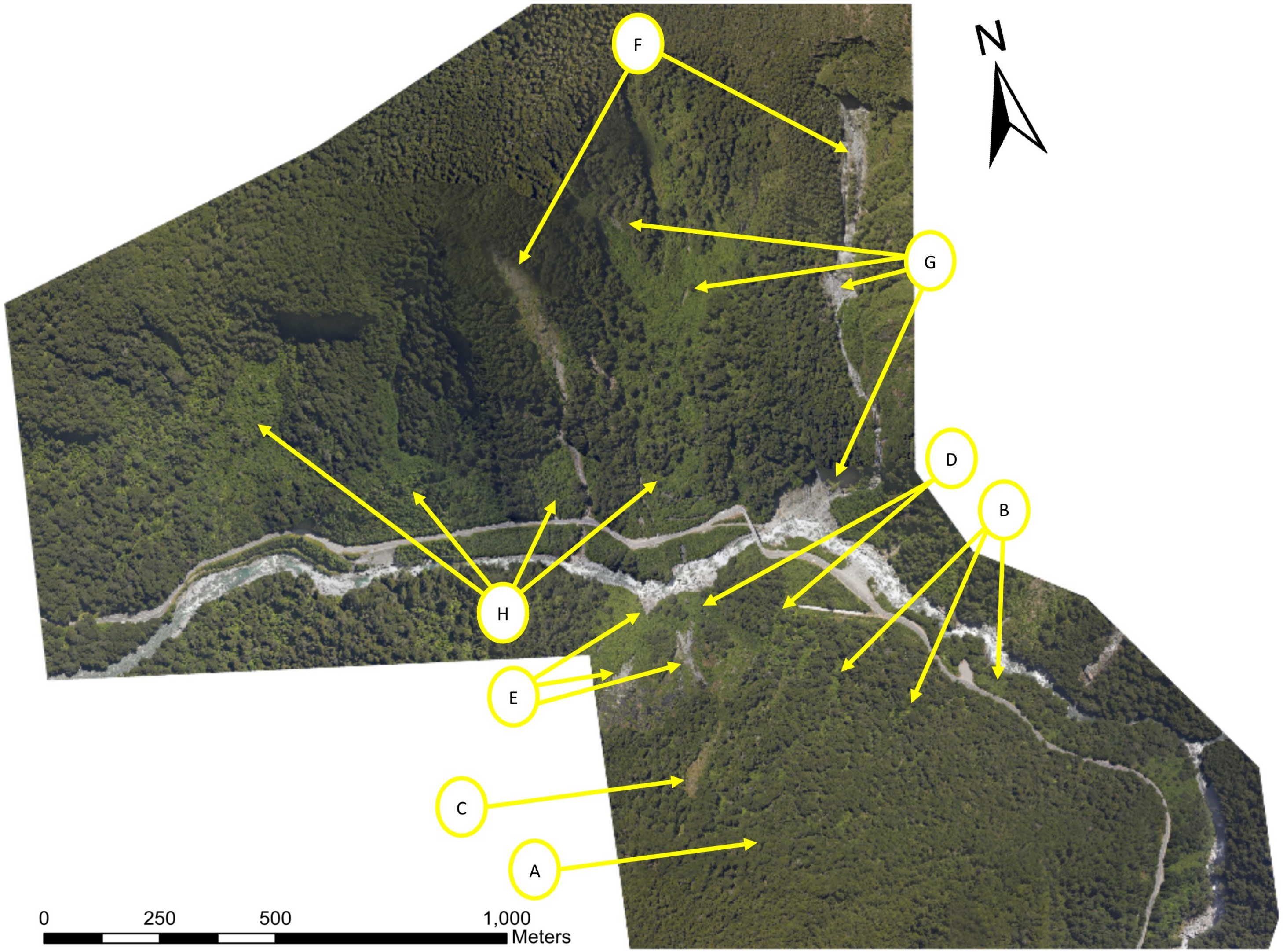

Figure 4.11: Aerial Photo of slopes above the highway between The Hinge and Thunder Creek Falls Car park. (A)Dense vegetation in the aerial photo appears as dark areas.(B)Patches of younger vegetation appear as the lighter green colours that appear lower than the surrounding vegetation.(C)Recent landslide where vegetation has been removed exposing schist rock.(D)Larger areas of younger vegetation appear near the highway bridge.(E)Areas where vegetation removal has exposed regolith.(F)Two areas where recent landslides and stream flow have exposed schist bedrock.(G)Areas of regolith material exposed beneath vegetation.(H)Very large areas of young vegetation on slopes above the highway west of Gates of Haast

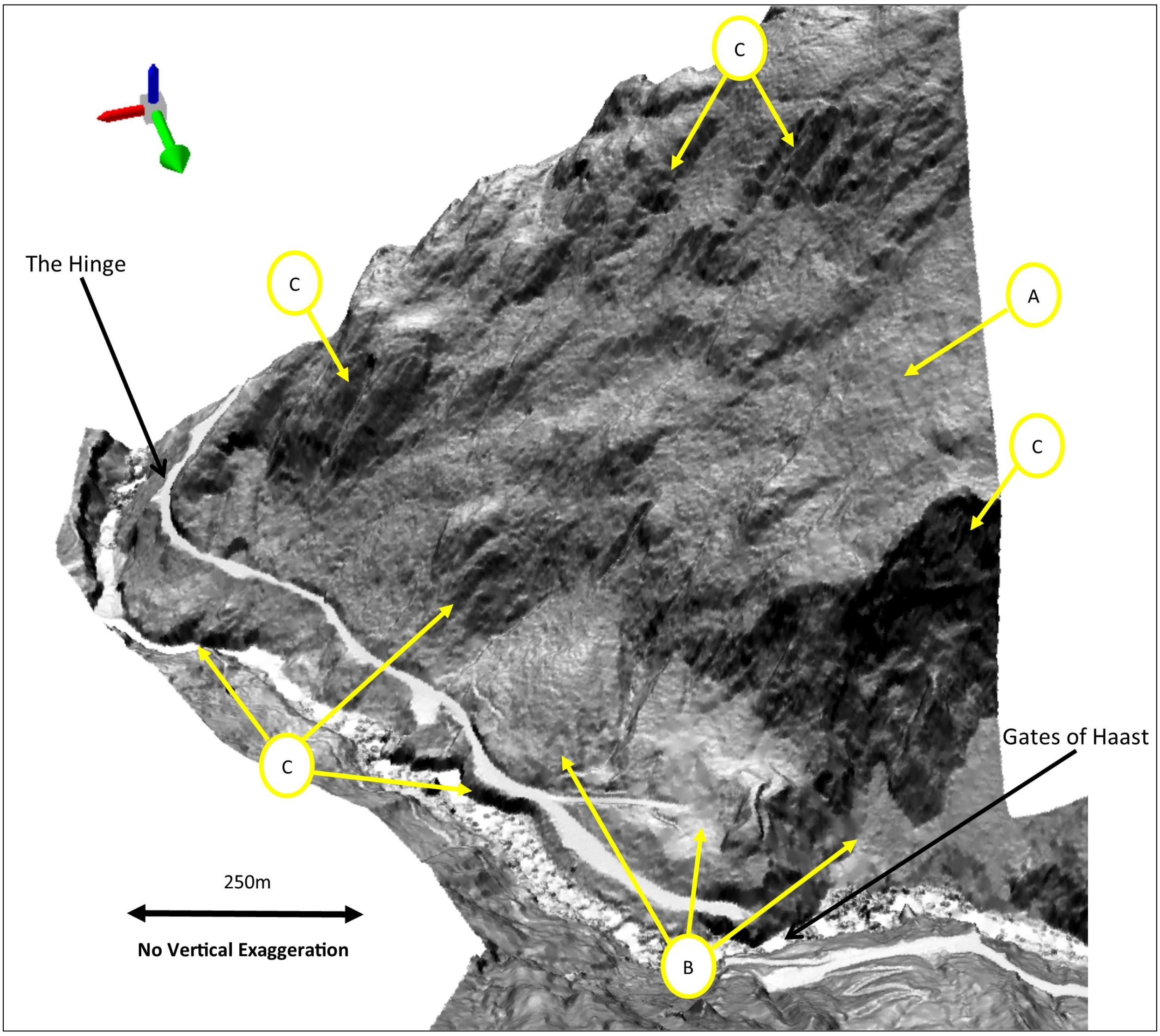

Figure 4.12: LiDAR model of the slopes between The Hinge and the Gates of Haast Bridge. (A)Rough undulating surface textures indicate regolith cover on upper slopes.(B)Larger deposits of regolith are present near the Gates of Haast Bridge.(C)Areas of bedrock identified by foliation lineations and the common orientation of cliff aspects.

4.4.2 LiDAR Surface Analysis

LiDAR model analysis of the slopes between The Hinge and the Gates of Haast Bridge indicate that the slope consists of a mix of bedrock and shallow regolith cover. The slope consists of a rough undulating surface texture that covers the lower slope and the majority of the mid and upper slopes (Figure 4.12 A). The rough undulating surface textures are confined to the lighter coloured areas representing relatively gently slopes. The rough surface textures represent deposits of regolith on the slope and are relatively thin with the exception of the regolith cover in the vicinity of the Gates of Haast Bridge that is thicker (Figure 4.12 B). The steeper slopes represented by the dark shading are largely absent of the rough surface textures visible on the rest of the slope and in some cases lineations are visible on these surfaces (Figure 4.12 C). These steeper areas represent bedrock cliffs with surfaces are orientated approximately east-west, aligned with a prominent and persistent rockmass defect, with the lineations visible on the surface a result of schist foliation. Overall the slope is covered by a thin layer of regolith with bedrock exposed in steep cliffs on the slope and particularly below the highway next to the river.

The slopes above the highway between the Gates of Haast Bridge and Thunder Creek Falls consists of a mix of bedrock and large deep deposits of regolith. The bedrock areas consist of steep cliffs shown as the dark areas in Figure 4.13A, but its the alignment of the cliffs that presents the clearest evidence that schist bedrock is exposed. The cliffs that are visible have a preferential orientation with surfaces striking north-south with surface aspects perpendicular to the slope. The preferential alignment of the cliffs is a result of bedrock foliation being the primary controller on the failure of bedrock and as a result the orientation of the cliffs. Using the bedrock textures it is clear that bedrock is present across most of the upper slope and in isolated areas in the mid to lower slopes where it is largely confined to narrow bedrock ridges(Figure 4.13 B). Next to and below the highway there is almost no bedrock exposed at the surface. Regolith cover is extensive across the lower slope with deposits extending into the mid slope but becoming thinner the higher up the slope they are deposited. The texture of the regolith cover in this area is very rough, undulating and irregular with the most significant deposits visible on the mid and lower slopes (Figure 4.13 C). The highway is this area is shown by the white flat surface running across the lower slope where it is almost entirely built on regolith (Figure 4.13 D).

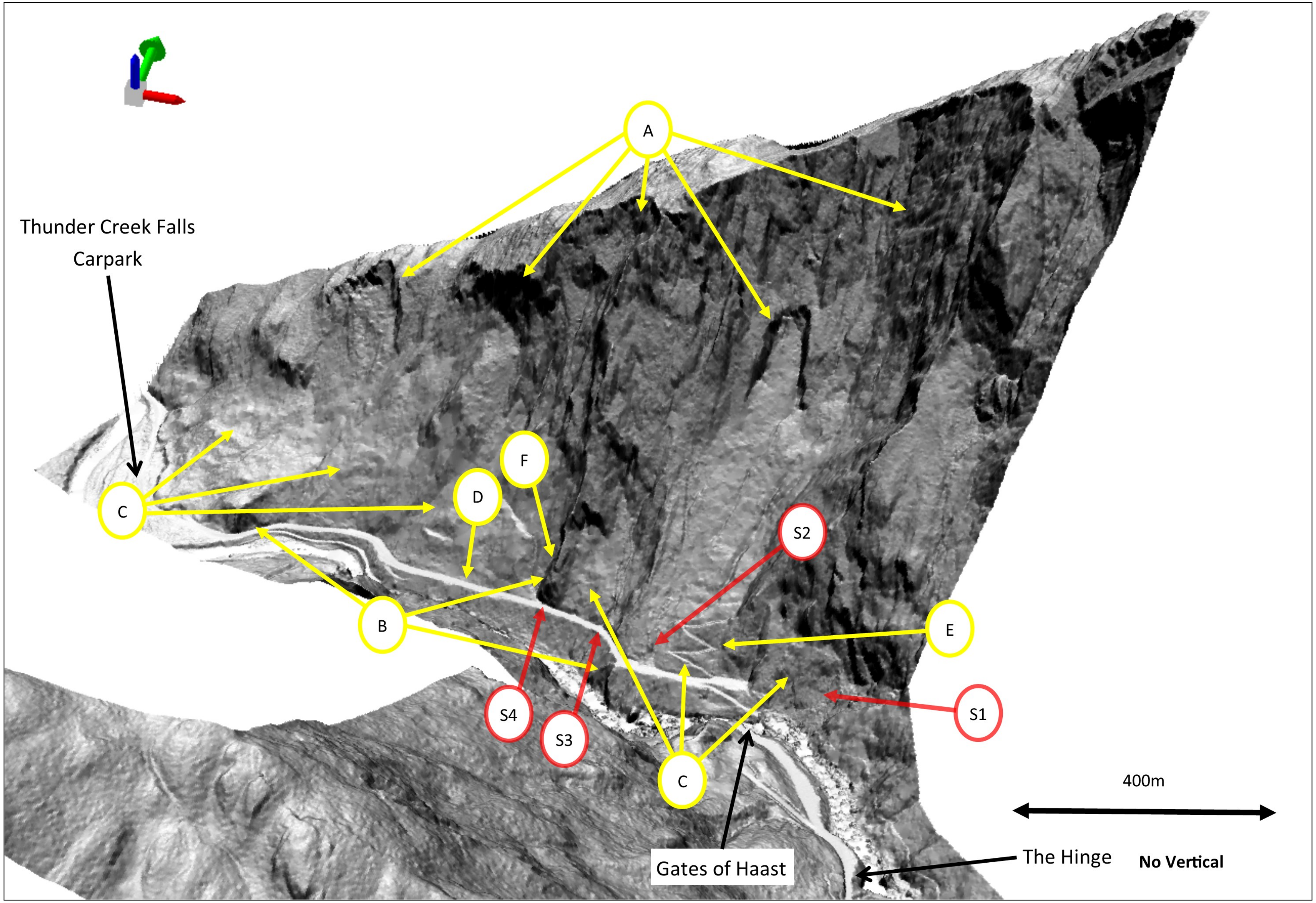

Figure 4.13: LiDAR model Slopeshade of the slopes between the Gates of Haast Bridge and Thunder Creek Falls car park. (A)Areas of Bedrock identified by the linear cliff orientations and the regular undulations.(B)Small exposure of bedrock at the base of the slope dominated by regolith.(C)Large thick deposits of regolith material covering the lower slopes.(D)State Highway Six cutting across the base of the slope over regolith deposits.(E)Zig zag pattern on this slope caused by a drainage track put in to divert the stream above.(F)Isolated ridge of schist bedrock on the lower slope. Ground truthing sites identified by the red arrows and S1,S2,S3,S4.

4.4.3 Ground Investigations

Ground investigations were undertaken at four sites between The Hinge and Thunder Creek Falls to validate the interpretations made in the air photo and LiDAR analysis. The opportunities to perform ground truthing in this area are very limited with this part of the pass being the most densely vegetated resulting the surface materials being completely obscured from ground level. The steepness of the terrain also made travel through the bush nearly impossible and as a result ground truthing sites were limited to areas next to the highway. The sites investigated consisted of; an area upstream of the northern bridge abutment, The Gates of Haast landslide, a small stream channel 250 metres downstream from the highway bridge and a cliff 400 metres downstream of the highway bridge (Locations shown in Figure 4.13 as S1, S2 S3 and S4 respectively).

The first site that is investigated (S1) between The Hinge and Thunder Creek Falls consists of the slope upstream of the northern bridge abutment. The slope at this location was observed from the aerial photography to lack vegetation coverage and appeared to be covered with regolith. Analysis of the LiDAR model indicated that the area free of vegetation and some of the area above consisted of a cover of regolith. Figure 4.14 shows an exposure of the material on the slope where it is possible to identify a number of different units. Most of the image is filled with unconsolidated material consisting of angular boulders of schist one to two metres across with smaller boulders, cobbles and gravels making up the matrix (Figure 4.14 A). The regolith in the left of the image appears to be part of an older regolith deposit and is actively being eroded by the river in times of flood (Figure 4.14 B). The regolith on the right hand side has been transported down slope by the creek just visible at the top of the image (Figure 4.14 C). In the centre of the image there is a large area of bare schist rock that has foliation orientations striking approximately north-south and dipping steeply (Figure 4.14 D). Given the foliation orientation is very close to that of the regional schist bedrock and the large size of the exposure it is almost certainly an exposure of schist bedrock partially covered by regolith.

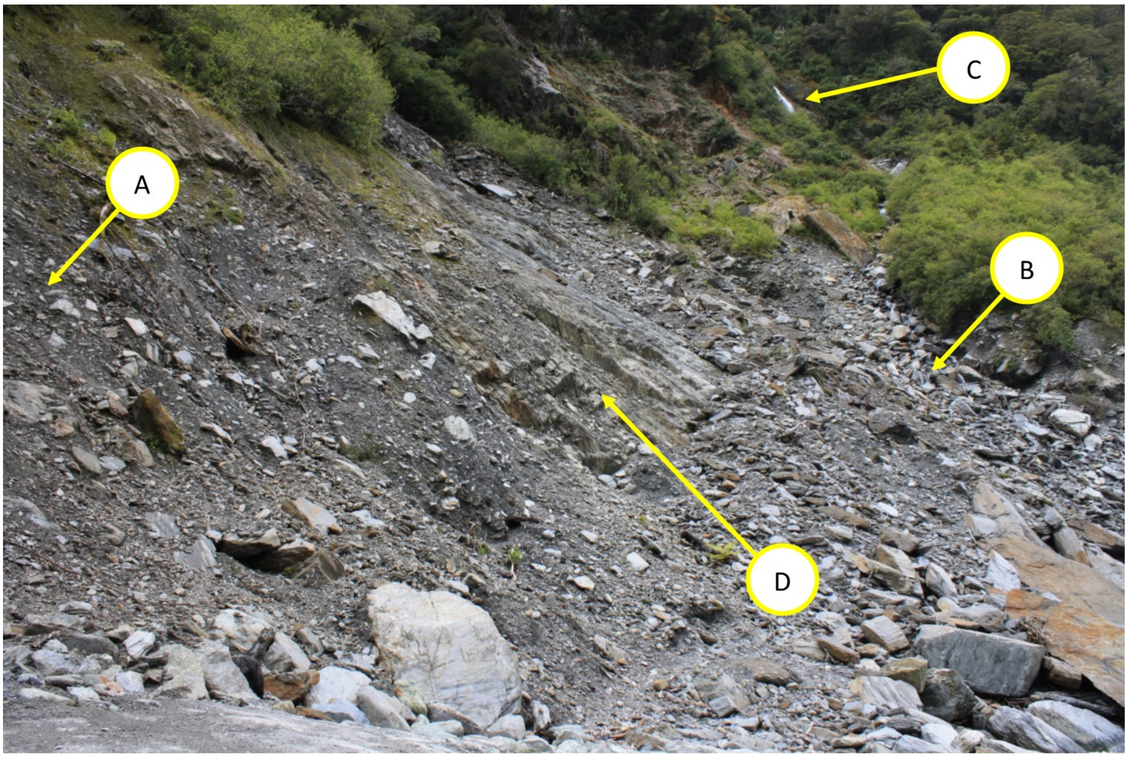

Figure 4.14: SITE 1. Regolith exposure on true right slope upstream of the Gates of Haast Bridge. A) Exposure of older regolith material above the river. B) fresh regolith material deposited by the stream is the back of the Image(C). D) Exposure of schist bedrock within the largely regolith covered slope. Foliation orientations closely match that of regional schist bedrock.

The second site to be investigated (S2) was situated on the western margin of the Gates of Haast landslide where a number of different surface units were observed. The aerial photo and LiDAR analysis indicated that the area was composed of schist regolith with steep bedrock cliffs on the eastern side and a small ridge of bedrock on the western side of the regolith deposit. The ground investigation revealed that the zig zag track seen in the LiDAR model (Figure 4.13 E) was the track used during remediation of the Gates of Haast Landslide and was used for drainage and pizeometer installation. From the track it was possible to identify the materials beneath the vegetation where the track had been cut into the slope. large boulders up to three metres across were visible on the slope surrounded in a mix of finer material as visible in Figure 4.15. Where the slope has been cut by the drainage track it is possible to see some of the matrix; it consists of platey cobbles of schist with a mix of fine to medium angular gravel sized particles as shown in Figure 4.16. The exposures observed at this site are consistent with a large deposit of regolith and are probably the result of debris slide and debris flow processes.

Figure 4.15: SITE 2a. Schist boulder approximately 2x3 metres across on the drainage track above the Gates of Haast Bridge.

Figure 4.16: SITE 2b. Regolith matrix material on the drainage track above the Gates of Haast Bridge

The third site to be investigated (S3) is located where a stream channel crosses the highway 250 metres west of the Gates of Haast Bridge. The site was interpreted in the LiDAR survey to be a relatively small deposit of regolith just west of the Gates of Haast landslide deposit. Figure 4.17 shows an exposure of the material making up the slope in the margins of the stream channel. The material consists of large boulders of schist rock up to four metres across with many smaller very angular boulders approximately one metres across. Between the boulders is a matrix consisting of angular cobbles and a mix of angular gravel sized particles and the proportion of matrix to boulders varies throughout the exposure. The material visible in the margins of the stream has been transported from further up slope through a combination of debris sliding and debris flows resulting in a deposit of colluvium largely obscured be vegetation but visible in the LiDAR model.

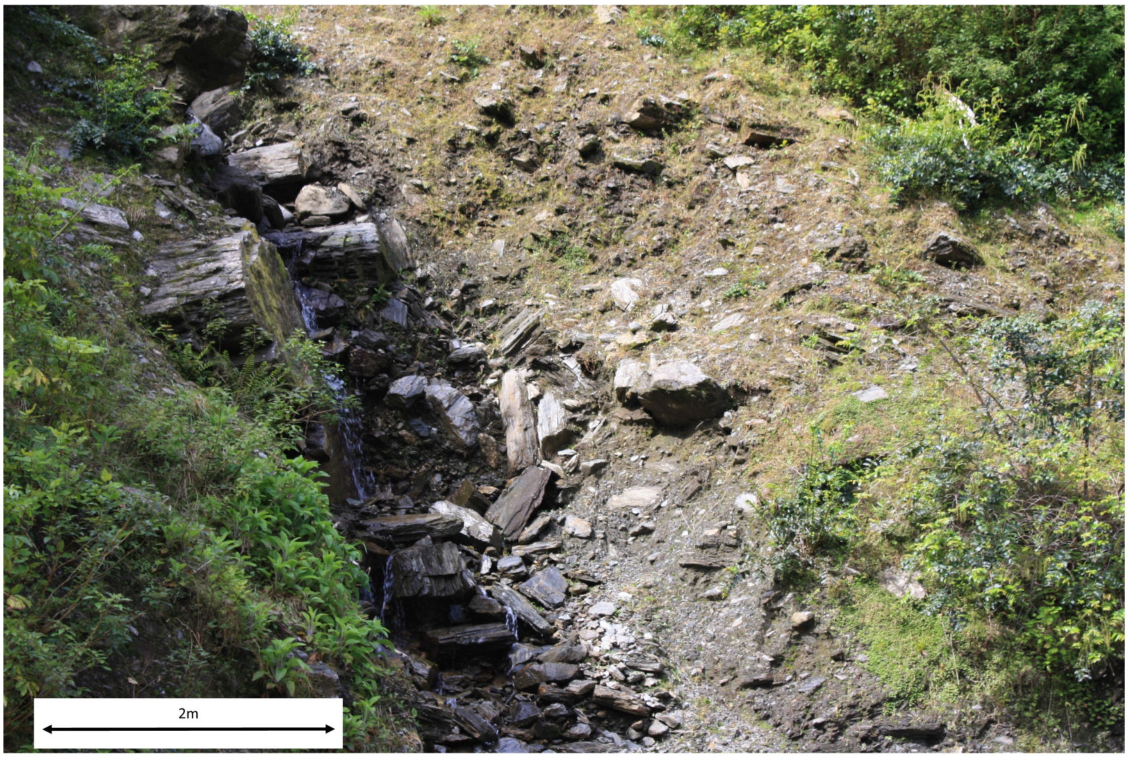

Figure 4.17: SITE 3. Exposure of regolith material in stream west of Gates of Haast Bridge.

The final site that was investigated (S4) consisted of a large schist cliff next to the highway 400 metres west of the Gates of Haast Bridge. Analysis of the LiDAR model indicated that the slope in this area consisted of a ridge of schist rock flanked by deposits of regolith (Figure 4.13 F). Figure 4.18 shows an exposure of schist rock at highway level where the schist rock ridge in the LiDAR model meets the road. Measurements of the foliation orientations of the schist rock revealed a strike of 025 and a dip of 66 degrees matching the regional foliation orientation and indicating that this exposure of schist rock is an exposure of bedrock and not a large displaced block. On both sides of the bedrock outcrop schist boulders up to three metres across were just visible in the vegetation indicating that a surface cover of regolith exists on both sides of the bedrock outcrop. The presence of bedrock at this outcrop supports the interpretation that the ridge observed in the LiDAR model is bedrock and that both sides of the deposit consist of regolith materials.

Figure 4.18: SITE 4. Rockmass outcrop next to highway west of the Gates of Haast Bridge. Measurements of the foliation orientations of the rockmass revealed a strike of 025 and a dip of 66 degrees matching the regional foliation orientation and indicating that this exposure is schist bedrock.

4.4.4 Geomorphological Interpretations

The slopes above the highway between The Hinge and the Gates of Haast Bridge are covered in a mix of regolith deposits with small outcrops of bedrock next to the river and highway. The lower portion of the slope is covered by a thick deposit of regolith material and has a lower average slope angle compared with the upper slopes. This area is marked in the geomorphology map in Figure 4.19 and is shown extending across most of the lower slope. A small amount of bedrock is visible just below the highway as well as in two locations next to the highway where regolith materials cover the top of the outcrop. On upper slopes the surface consists of a thin cover of regolith extending across the entire slope with cliffs of schist bedrock scattered throughout the slope; most of these cliffs are aligned with a prominent rockmass defect and the face of the cliffs point across the slope resulting in the formation of small gulleys. The regolith materials covering the upper and lower slopes originate from landsliding of the bedrock cliffs and remobilisation of the resultant regolith materials likely through a combination of debris sliding and debris flows. Direct observations of recent landslides is visible in the aerial photography in a small number of locations while indirect observations from the relative ages of vegetation indicated that a larger portion of the slope has been subjected to landslides in the recent past.

Between the Gates of Haast Bridge and Thunder Creek Falls the highway crosses beneath slopes composed of both bedrock and variable thickness's of regolith. The slope below the highway is almost entirely composed of regolith with only small areas of bedrock, most at river level, visible from the LiDAR imagery. The lower portion of the slopes above the highway are almost entirely compose of thick deposits of regolith with small ridges of bedrock separating the largest regolith deposits. The extent and size of the regolith deposits and the bedrock ridges is shown on the geomorphology map in Figure 4.19, illustrating just how extensive the regolith cover is in this zone. The upper portion of the slope consists of steep bedrock areas with numerous cliffs and some thinner deposits of regolith. These steep areas of bedrock appear to be unstable with recent rockfall visible in aerial imagery contributing to the build up of regolith material. The areas of regolith material also correspond to areas of relatively young vegetation indicating that the slopes above the highway are in a state of marginal stability and have been subjected to debris slides and/or debris flows in the past.

4.4.5 Slope Hazard Identification

The geomorphological interpretations primarily based on LiDAR model analysis highlights the hazards that the highway is exposed to in this zone. They include debris flows, debris slides, rockfall, and deep seated gravitational failures with almost the entire zone susceptible to one or more of these hazardous slope processes. A summary of the areas affected by each slope process as well as an evaluation of the likelihood of these processes affecting the highway is provided below:

1. **Rockfall:** The steep bedrock areas identified in the geomorphic analysis of this area are the most unstable areas in the pass. It was possible to see recent rockfall events in the aerial imagery and the presence of large deposits of regolith material beneath indicate a very active slope. A recent rockfall visible on the slope west of the Gates of Haast Landslide reached and crossed the highway presenting a very large hazard to the highway.

2. **Debris Flows and Slides:** With large areas of the slopes in this zone covered with re-

golith the potential for debris slides and flows is considerable. The zone has previously been subjected to debris flows and slides recorded since the highways construction with indirect evidence of variable vegetation ages suggesting that large areas of regolith material are in a state of marginal stability.

3. **Deep Seated Debris Sliding:** Instances of deep seated debris sliding of the regolith deposit just west of the gates of Haast bridge has been recorded in previous engineering investigations (Opus 2001, 2002), but the areas subjected to this deep seated sliding was unable to be identified at the large scale geomorphology mapping scale of 1:8000 to 1:10000. The area does however show clear signs of large scale active slope processes and the overall morphology of the area suggests that it is unlikely to be stable. For this reason this area is investigated in detail in Chapter 5.

4. **Highway Collapse:** Where the highway has been built partially or fully across regolith deposits, and where the Haast River is eroding the toe of the slopes the potential exists for highway collapse ot occur. These conditions appear to exist west of the Gates of Haast bridge with isolated areas not built on bedrock potentially suceptable between the bridge and The Hinge.

4.5 Synthesis

The aim of this chapter was to identify the surface units, slope processes and potential landslide hazards on the slopes above the highway in the northern zone. LiDAR was able to reveal that the slopes between Pipson Creek and Thunder Creek Falls are composed of a mixture of deep regolith deposits, regolith mantled slopes and bedrock dominated surfaces. Small areas displayed active slope processes where recent mass movements had revealed the material beneath. Many other areas of the slope showed signs of recent activity with young vegetation providing evidence that slope processes are probably an on going issue. The entire length of the northern zone is exposed to at least on potential hazard with many sections exposed to one or more potential hazards including debris flows, debris sliding, rockfall, highway collapse and deep seated gravitational slope failures. The northern zone appears to be far more hazardous than the southern zone and as such the four sites selected to be studied all all located in the northern zone. They consist of Diana Falls, Ford Creek, The Hinge and the Gates of Haast and are studied in more detail in Chapter 5. The potential impacts of the hazards identified in this chapter are discussed in more generally in Chapter 6 along with comment on the best ways in which to manage them.

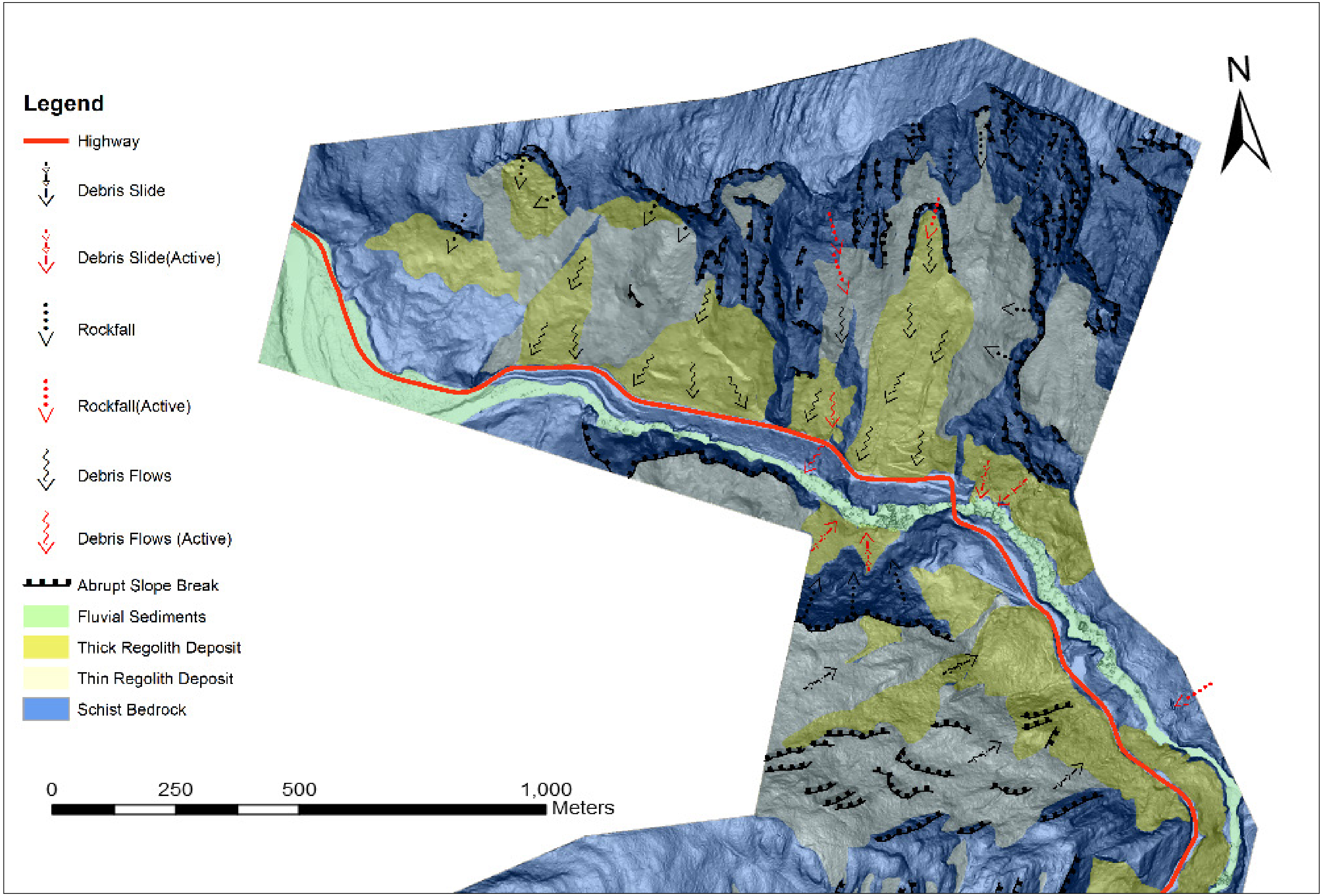

Figure 4.19: Geomorphology map of slopes above the highway between Pipson Creek and The Hinge.

Chapter 5

Detailed Evaluation of Selected Hazardous Slopes

5.1 Introduction

This chapter presents the investigation of four sites within the northern zone of the field area using high resolution remote sensing techniques, to provide the most complete picture of the sites to date. The location of the investigation areas is indicated on the LiDAR surface map in Figure 5.1 with the extent of investigation shown by the four yellow boxes focusing on Diana Falls, the Ford Creek Landslide, The Hinge and the Gates of Haast. Diana Falls, The Hinge and the Gates of Haast have all had a history of landslide activity and all displayed signs of significant mass movement processes in the Northern Zone large scale geomorphology and hazard identification chapter. It is important to investigate these sites as they appear to be based on large scale observations, providing the greatest hazards to the highway. The resolution of the LiDAR survey, in particular, can provide new insights into the nature of the ground beneath highly vegetated and otherwise inaccessible slopes. The goal of this chapter is to identify the distribution of geomorphic units, identify evidence of landslide activity, build up a picture of the subsurface and understand the processes on a small scale that have shaped the slope and may influence further changes at the four sites in the future.

5.2 Detailed Evaluationof Diana Falls

5.2.1 Site Overview

The Diana Falls site includes the slopes within the large landslide scarp above the 2013 Diana Falls landslide, and the areas immediately outside of the scarp that were identified as hazardous (see Chapter 4). This site was investigated as it has been identified as an area of recent instability, has a history of landslides, and appears from the large scale geomorphology mapping (see Chapter 4) to be a significant hazard to the highway. The site has been investigated using high resolution LiDAR imagery combined with aerial photography to identify the material covering the slope and reveal landslide features indicative of ongoing mass movements. No ground investigations were possible above the highway cliffs without the aid of an experienced abseiler, and dense vegetation made identification of the larger scale landslide features difficult from the ground.

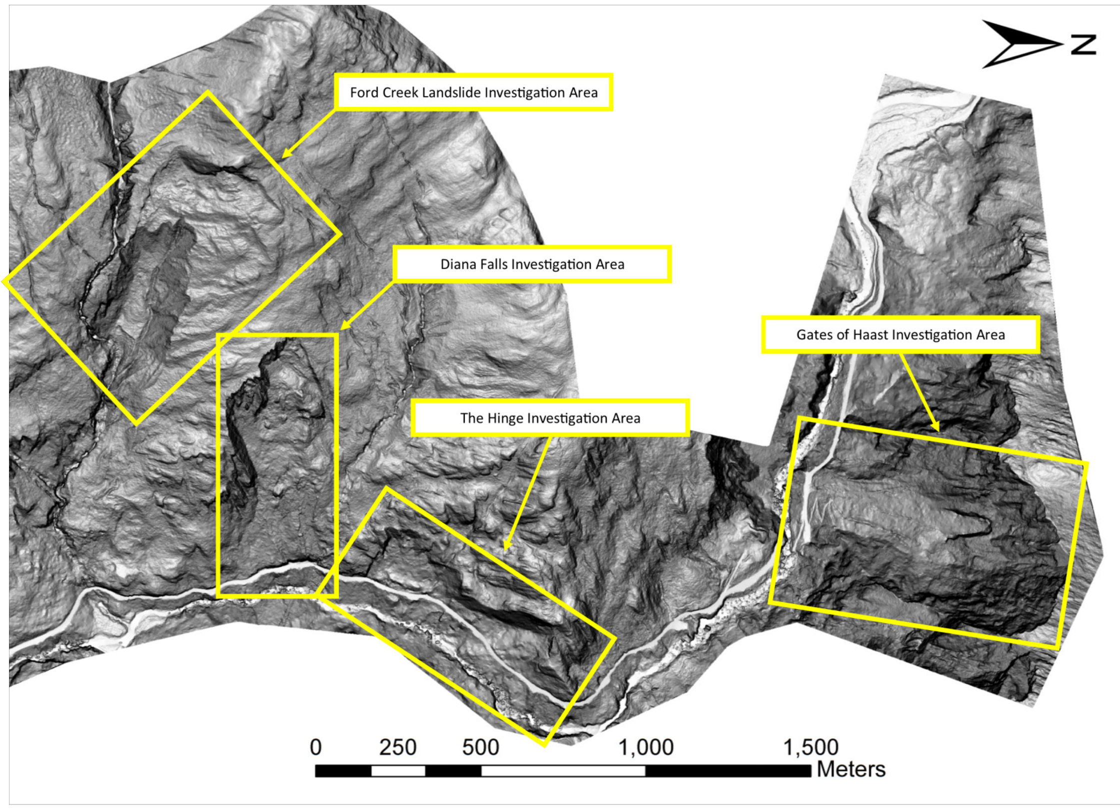

Figure 5.1: Location of engineering geomorphology investigation areas

5.2.2 Surface Units

Small parts of the area around the Diana Falls landslide complex are composed of schist bedrock. Analysis of the LiDAR surface shown in Figure 5.2 revealed that foliation-aligned undulations located above the main landslide headscarp, and on the southern side of the southern lateral scarp. The headscarp (Figure 5.2 A) and southern lateral scarp (Figure 5.2 B) consist of steep cliffs of schist bedrock ranging from 20 to 100 metres high, with a number of parallel cliffs midway up the slope likely formed by a second persistent set of parallel rockmass defects (Figure 5.2 C). Bedrock is also visible at road level where the highway has been cut into the slope, exposing numerous sets of foliation planes with foliation attitudes conformable to regional bedrock, and is visible in the LiDAR surface as the very dark areas next to the bright highway. Within the confines of the large landslide scarps, exposures of bedrock are rare with only two locations where rock masses are identifiable. These are visible within the large landslide in the LiDAR surface (Figure 5.2 H) as a steep cliff near the top of the large landslide and another cliff just to the south of the Diana Falls Headscarp. The rock masses may be exposures of schist bedrock, but given that they are situated within a largely regolith covered slope and surrounded by landslide scarps it would be more realistic to consider them to be large displaced blocks of schist.

A variable thickness of regolith material covers almost the entire slope within the large landslide scarps, with a thin veneer of material to the north. A rough irregular texture is present across the entire slope within the large landslide scarp and on the slopes to the north of the northern lateral scarp. Rough irregular textures are visible between the highway and the river, where they cover the entire slope with the exception of two isolated areas of bedrock. The rough irregular texture is indicative of regolith cover and in the context of large landslide scarps is most likely landslide debris from previous landslides that have occurred in the past given the large scarps. With the exception of the two areas of bedrock above the road, and the bedrock cliffs next to the highway, the entire slope above the highway within the large landslide scarp consists of unconsolidated landslide debris sourced from previous failures. The distribution of regolith materials within the investigation area is shown on the map in Figure 5.3.

5.2.3 Landslide Features

There is clear evidence from the slope morphology that large areas of the Diana Falls investigation have been subjected to landsliding in the past. With the use of LiDAR, landslide features on this slope are more easily recognised. The clearest indication of past landslide events is the presence of the prominent head scarp and lateral scarps of a large landslide encompassing most of the investigation area. The headscarp and lateral scarps of the large landslide are visible as the abrupt steps in slope in the LiDAR surface, appearing as the dark areas at the top and southern side of site (Figure 5.2 A and B); given the slope angle of between 55 and 65 degrees, the height of the scarps and that bedrock is present above and on the southern side, the scarps are composed of bedrock. On the northern side of the investigation area a smaller lateral scarp, parallel to the southern lateral scarp, is visible ranging in height from two to ten metres (Figure 5.2 G). The slope angle and height of the scarp strongly suggests that the scarp is composed of bedrock rather than regolith. Both the northern and southern lateral scarps, strike parallel with one another and also align with the cliff faces just to the south of the southern lateral scarp, a similarity that suggests they are failing along a persistent and spatially continuous rockmass defect other than foliation.

Within the boundary of the large landslide scarps a number of secondary scarps are present within the regolith covering the slope. The two recorded landslides on this slope involved failure of the regolith material through debris slides, with the first event in the 1970s and the second in 2013 at Diana Falls (Opus 2013b). The location of the recent Diana Falls failure is easily identifiable in the LiDAR surface with well defined lateral scarps and a number of headscarps visible and annotated in Figure 5.2 L. The headscarp of the 1970s landslide is very subtle and the extent is indicated on the map in Figure 5.3. The area between Diana Falls and the 1970s landslide has the greatest concentration of secondary scarps and laterals scarps on the entire slope. These secondary scarps are visible in the LiDAR surface as the steps in slope that appear darker than the surrounding material (Figure 5.2 D). Connected to these secondary scarps are three more linear features that extend down slope to the cliffs above the highway (Figure 5.2 E); These linear features are likely to represent the lateral scarps of the moving regolith material. These scarps are well defined and the highest of the three scarps extends across the top of the recent Diana Falls failure indicating that the slope above and to the south of Diana Falls is in a state of marginal stability.

5.2.4 Slope Subsurface Interpretation

Understanding the subsurface of the Diana Falls landslide is very important to assess the current and future stability of the slope. Based on the surface expression of the landslide in the LiDAR surface it is possible to create two scenarios that would result in the surface expression observed.

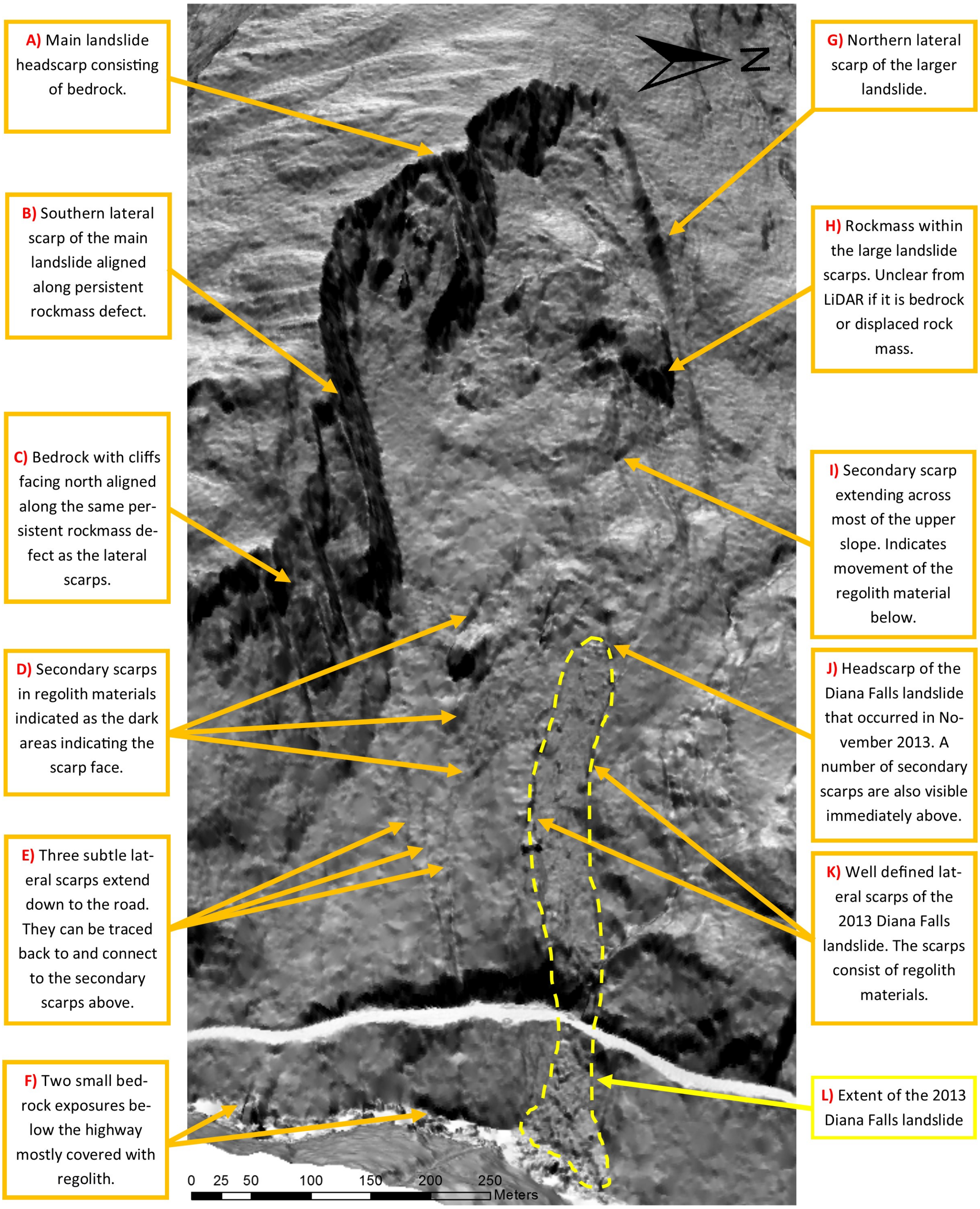

Figure 5.2: Oblique view of the LiDAR surface of Diana Falls landslide Complex with an orientation looking 270 degrees and 25 degrees from horizontal. Annotations indicate the major features visible on the surface of the slope. The

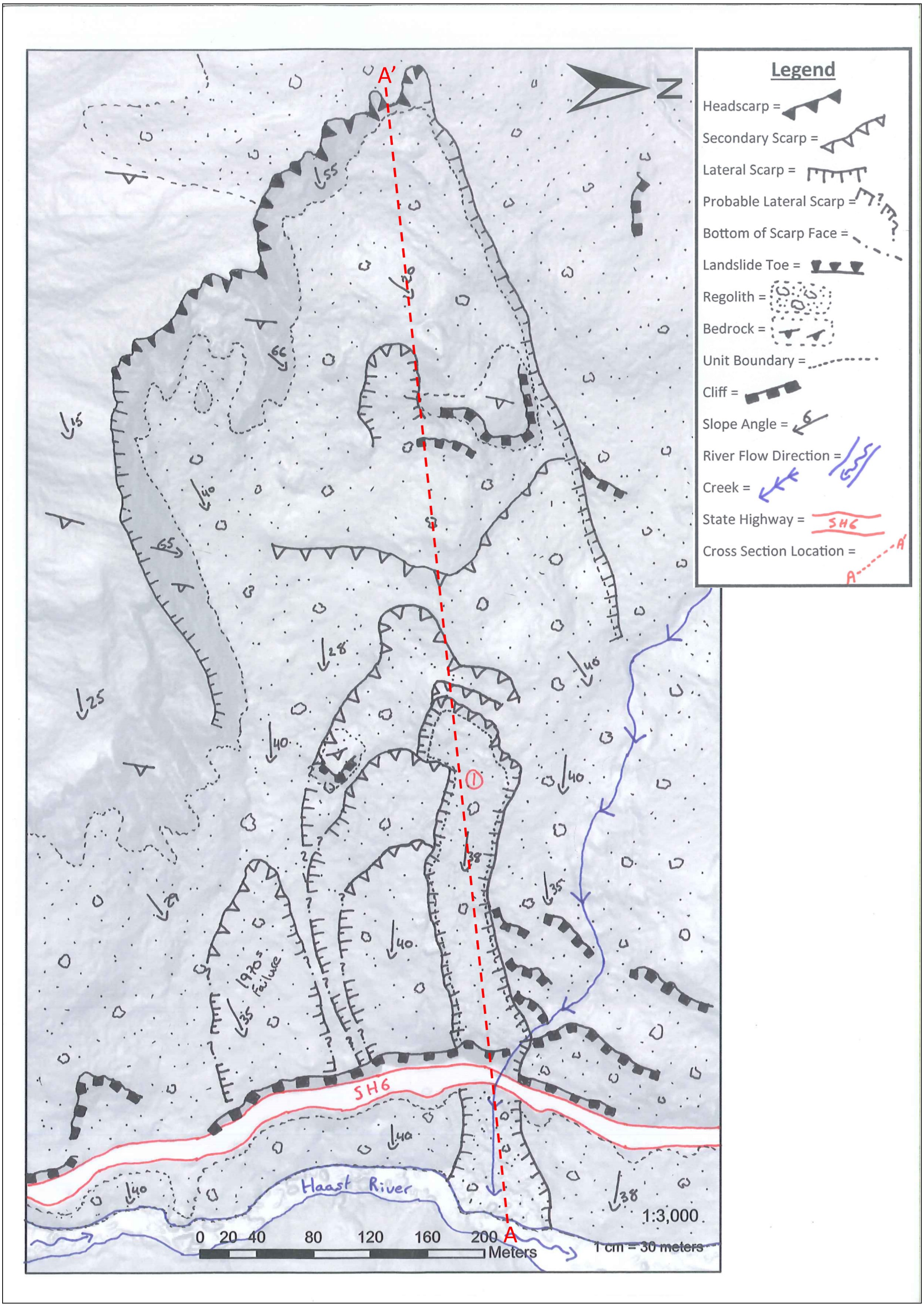

Figure 5.3: Engineering geomorphology map of the Diana Falls Landslide Complex showing the distribution of bedrock and regolith materials and landslide features.

A realistic interpretation of the geometry of the two scenarios is shown in schematic cross sections in Figure 5.4, which shows how the features identified in the LiDAR surface, aerial photography and previous engineering reports can be reasonably interpreted and projected below ground. The interpretation is provided as two extreme scenarios that could form the surface expression seen in the LiDAR surface and fit with observations made during the initial engineering investigations by Opus (2013a), however, one of the scenarios is more probable based on the LiDAR observations.

The first scenario for the Diana Falls investigation area infers that the main landslide scarps are the result of displacement of a large landslide body with a deep failure surface (An interpretation of this scenario is shown as Scenario One in Figure 5.4). There are a number of rockmass defects within the schist bedrock that facilitate the failure; Three main persistent defects include foliation (dipping east at 70 degrees), defect one comprising the lateral scarps (dipping north/south and dipping near vertical) and defect two (dipping east at around 10 degrees). In this scenario foliation and defect two provide the basal failure surface with defect one acting as the third plane to facilitate failure. As a result of the basal failure surface following foliation and defect two the surface is stepped with large schist blocks being displaced and sliding down slope. In this scenario the large rockmass observed at the top of the 2013 Diana Falls landslide is a large schist block that has slid down slope, but has not rotated and still has foliation orientations similar to bedrock. It is conceivable that total displacement of the blocks has been relatively small and that most blocks would still have foliation orientations similar to bedrock. Given the very large and continuous schist rockmass observed a highway level the failure surface probably outcrops above the highway cliff exiting along defect two at a shallow angle.

The second scenario for the Diana Falls investigation area infers that the regolith material covering the slope within the landslide scarps is thin and that the rock masses within are exposures of schist bedrock (This scenario is shown as scenario two in Figure 5.4). In this scenario bedrock is exposed at or very near the surface with failures controlled by rockmass defects resulting in relatively small scale sliding failures. This results in the build up of a thin cover of regolith down slope of the bedrock exposures ranging in thickness from five to ten metres. In this case the rockmass at the top of the 2013 Diana Falls landslide, and near the top of the slope are exposures of intact bedrock with the rest of the slope consisting of shallow bedrock.

There is considerable uncertainty involved with the extrapolation of landslide subsurface geometry from its surface expression. Complete understanding of the true nature of the landslide failure surface cannot be accurately determined without a subsurface investigation but it is possible to narrow down the range of probable scenarios. It is more realistic that the failure surface is closer to scenario one than scenario two given the context of the large landslide features and the highly disturbed nature of the material within. The only way to truly understand the nature of the subsurface is to undertake more complete surface mapping combined with a subsurface drilling programme, but until then the most realistic interpretation is a slope closer to scenario one than scenario two.

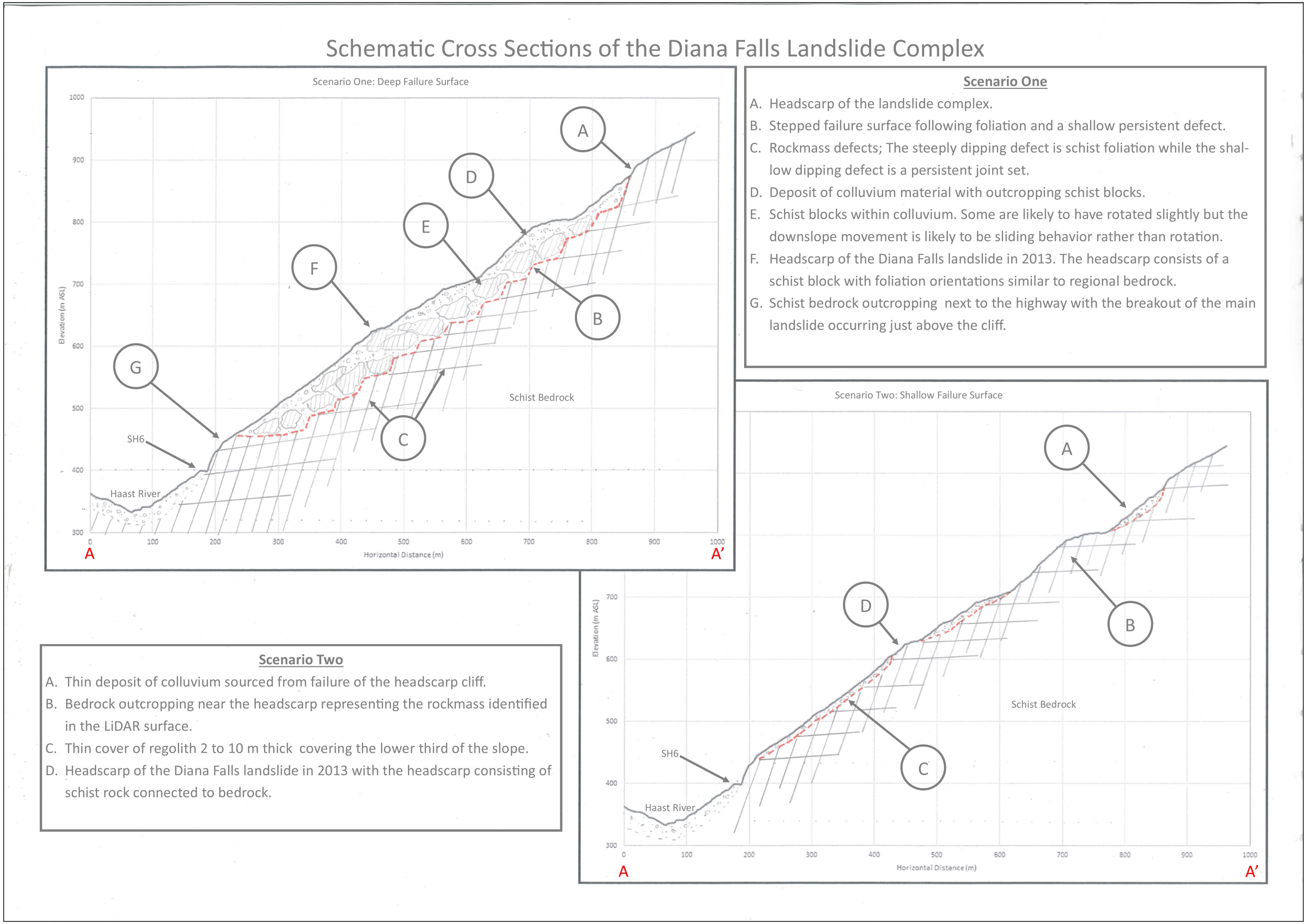

Figure 5.4: Diana Falls interpretative crossections

5.2.5 Landslide Processes

Based on the observations made and interpretation of the surface material covert type and the landslide features it is possible to identify three main failure modes active on the slope. They include;

1. **Debris Sliding**
    - Debris sliding events are the most significant and hazardous events to have occurred with case studies of debris slides occurring in the 1970s and more recently at Diana Falls. In the case of the Diana Falls failure historic aerial photography showed the slow development of the slope as ongoing debris creep indicated the gradual destabilisation of the slope before the failure.
2. **Debris Creep**
    - Evidence of debris creep is apparent in the LiDAR surface where secondary and lateral scarps are visible within the regolith materials that blanket the slope. The secondary scarps and lateral scarps are formed as a result of down slope movement of the material along a shear surface; the shear surface is likely to be either the bedrock-regolith interface or a shear within regolith materials.
3. **Rockfall**
    - There is evidence from the 2013 Diana Falls landslide investigation (Opus 2013a) and in the aerial photography that rockfall events have occurred on the slope. Evidence of rockfall from the large landslide headscarp and southern lateral scarp is visible in the aerial photo (Figure 5.5) with rockfall from rock masses within the regolith materials noted in the Diana Falls landslide investigation report.

5.2.6 Present Slope Stability

There are indications in the LiDAR surface, and from aerial photography, that parts of the upper slope consisting of the headscarp, lateral scarps and regolith materials above Diana Falls are potentially unstable. The southern end of the headscarp of the large landslide show signs of relatively recent failures with large boulders and fresh unconsolidated regolith materials are visible surrounded by young vegetation (Figure 5.5 A). Both lateral scarps are covered by dense vegetation and from aerial photography show no signs of recent instability, with the exception of one area near the headscarp on the southern lateral scarp (Figure 5.5 B). It is difficult to determine whether the scarps identified in the regolith materials are active from the aerial photos as dense relatively mature vegetation covers the regolith areas of the upper slope. The only area where past regolith movements are visible on the upper slope is on the southern side of the landslide beneath the lateral scarp where relatively young vegetation indicates recent instability (Figure 5.5 C). Overall the areas above the Diana Falls show signs of instability with some relatively small recent failures visible in aerial photography. It was not possible to determine the activity of the scarps visible in the LiDAR surface, as dense vegetation obscures visible signs of recent movement.

The lower portion of the Diana Falls investigations area, encompassing the areas down slope of the Diana Falls headscarp, show clear signs of recent and ongoing landslide activity. The most obvious sign of mass movement activity on the lower slope is the Diana Falls landslide that is clearly visible in the aerial photo in Figure 5.5. The headscarp area of the Diana Falls landslide is clearly unstable in the aerial photo with debris and boulders visible as well as a number of secondary scarps within the unconsolidated materials (Figure 5.5 D). The area that failed in the 1970s is clearly visible as the area to the south of Diana Falls that is covered by relatively immature vegetation (Figure 5.5 E). This area appears to be recovering with no visible active landslide features in aerial photography and only potential landslide features observed in the LiDAR surface, that are likely to be the headscarps and lateral scarps of the 1970s failure. From the aerial photography and LiDAR surface analysis the area around the 1970s landslide does not show signs of recent movement, however, the areas above the Diana Falls headscarp do appear to be unstable with active scarps visible in air photos and more secondary scarps up slope visible in the LiDAR surface.

The area between Diana Falls and the 1970s landslide shows signs that it is a marginal state of stability. Analysis of the LiDAR surface revealed a number of secondary scarps running through regolith materials sourced from previous landslides. Given that the scarps are formed in regolith materials it is likely that debris creeping processes are acting on this part of the slope. Analysis of aerial photos provides some indications of the activity of these scarps, with the lowest two scarps corresponding to areas of relatively young vegetation (Figure 5.5 F). The presence of the young vegetation in the same location as the scarps indicates that movement has taken place recently and is likely to be an ongoing processes with debris creep continuing. The area between the Diana Falls and 1970s landslide shows indications of being unstable with the large scarp extending across the top of Diana Falls suggesting that both Diana Falls landslide and the slope immediately to the south are part of a larger landslide.

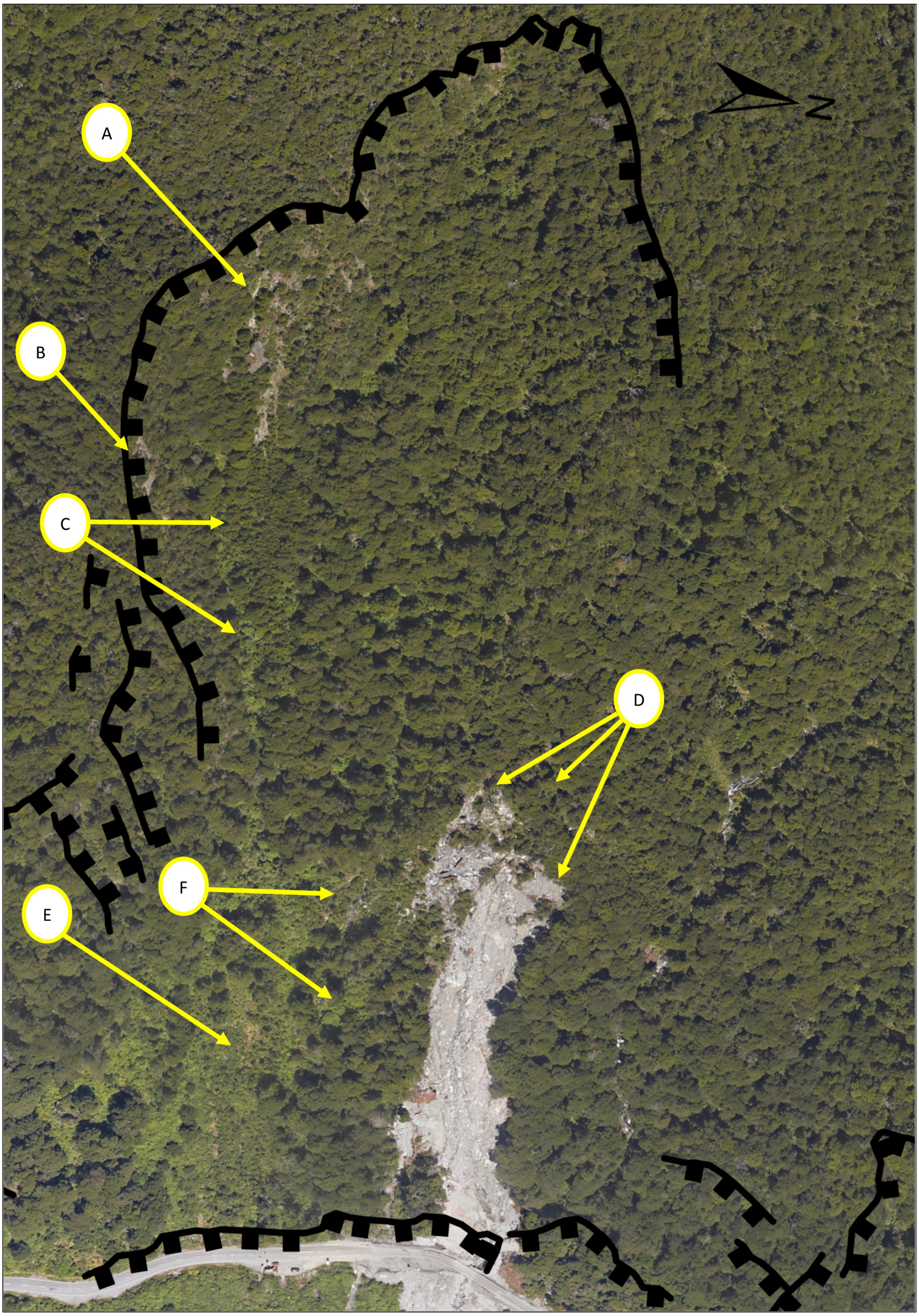

Figure 5.5: Aerial photo of the lower section of the Diana Falls landslide complex. The 2013 Diana Falls debris slide is clearly visible as the grey material extending above and below the highway. Large schist boulders are visible at the headscarp and measure up to 10m across.

5.2.7 Future Slope Development

Based on the observations from the aerial photography and LiDAR surface the potential for further debris slides and rockfall from within the large landslide scarps is certain. The analysis of the LiDAR surface revealed that most of the slope is covered with regolith materials particularly the areas between the 1970s and Diana Falls landslides, and the slope above the current Diana Falls Headscarp. Within these regolith materials numerous laterally continuous secondary scarps were identified indicating that the regolith on the slope has been subjected to movements in the past. In the area between the 1970s and Diana Falls landslide sites the scarps identified in the LiDAR surface also correspond with breaks in the vegetation indicating that these features have been recently active. The appearance of these recently active secondary scarps indicates that the area remains in a marginal state of stability and is likely to continue to move into the future and potentially develop into a large debris slide similar to Diana Falls. The loss of material at Diana Falls is likely to have an effect on the materials above the headscarp with the large secondary scarp above potential reactivating/accelerating. If this happens, it is likely that the regolith materials above will begin to creep and may potentially fail. The regolith covering the slope provides a source of material for future landslides and indications are that areas outside of the recent Diana Falls landslide are subject to creeping mass movements.

A major barrier to fully understanding the the current behaviour of the entire slope and thus being able to anticipate future landslide evolution is the lack of information on the subsurface geometry of the larger landslide. As discussed in section 5.2.4 there are a range of potential subsurface configurations that could produce the expression seen in the LiDAR surface. This wide range of potential subsurface configurations introduces considerable uncertainty into anticipating future landslide development. If the slope consists of a shallow cover of regolith with bedrock near the surface and exposed in cliffs then future failures are likely to only involve rockfall and debris sliding events similar to the one seen at Diana Falls. If, however, the regolith cover is deeper with rock masses exposed at the surface being displaced blocks rather than bedrock then the implication is that future landslides could be much larger and involve much more material than has been previously been observed. Crucially, the lack on information on the nature of the subsurface makes evaluation of the landslide potential of the Diana Falls investigation area as a whole incomplete until more information is available.

5.3 Detailed Evaluation of the Ford Creek Landslide

5.3.1 Site Overview

The Ford Creek site consists of the upper slopes north of Ford Creek and above the large landslide Headscarp at Diana Falls. The exact location and extent of the investigation is shown in Figure 5.1 and encompass the very large landslide feature identified for the first time during the large scale geomorphological mapping of the northern zone (see chapter 4). The site is situated on the upper slopes just north of Ford Creek and above the Diana Falls investigation area. The site was prioritised for investigation due to the very large size of the disturbed bedrock area, lack of information due to its newly discovered nature and potential impact that it could have on the highway. LiDAR is the primary tool used to investigate the area as the steep terrain and distance from the highway made any investigations on foot impossible without helicopter access and aerial photography reveals very little about the site due to the dense vegetation cover.

5.3.2 Surface Units

Schist rock is the dominant Geomorphic unit within the Ford Creek investigation area composing most of the slope with the exception of a number of isolated deposits of regolith. Parallel foliation aligned undulations are visible across most of the slope indicating that the majority of the slope consists of schist bedrock. Exposures of schist bedrock are visible in the steep gorge that Ford Creek flows in with the exception of one area at the base of a regolith deposit (Figure 5.9 C). Cliffs within the investigation are inferred to be exposures of schist bedrock with a large cliff at the top of the slope, as well as a number of smaller cliffs down slope having aspects and slope angles conformal to regional bedrock foliation (Figure 5.9 A and Figure 5.6 C). Isolated cliffs on the southern side of the investigation area just north of Ford Creek also appear to have a preferential orientation but do not follow bedrock; They appear to be following another persistent steeply dipping slope parallel rockmass defect, most likely a joint set (Figure 5.6 A).

Deposits of regolith material are present within the investigation area but are confined to two isolated deposits. Rough irregular textures indicative of regolith deposits are located just below the large cliff at the top of the slope as well as in the large depression just north of Ford Creek (Figure 5.6 C and E). Across the rest of the investigation area deposits of regolith appear to be thin with bedrock controlling the surface morphology. The regolith material at the top of the slope at the base of the large cliff is likely to be a rockfall deposit scoured from the cliff above. The regolith material filling the depression is quite extensive and appears to be quite deep based on the surface expression. Given the morphology of the depression the material has likely been deposited by debris slides/debris flows with material sourced from the steep sides of the depression.

5.3.3 Landslide Features

There are a number features in the LiDAR surface that indicate the presence of a large deep seated landslide on the slope just north of Ford Creek. The most prominent feature is the steep cliff at the top of the slope ranging in height from 60 to 80 metres in height (Figure 5.6 C). The headscarp

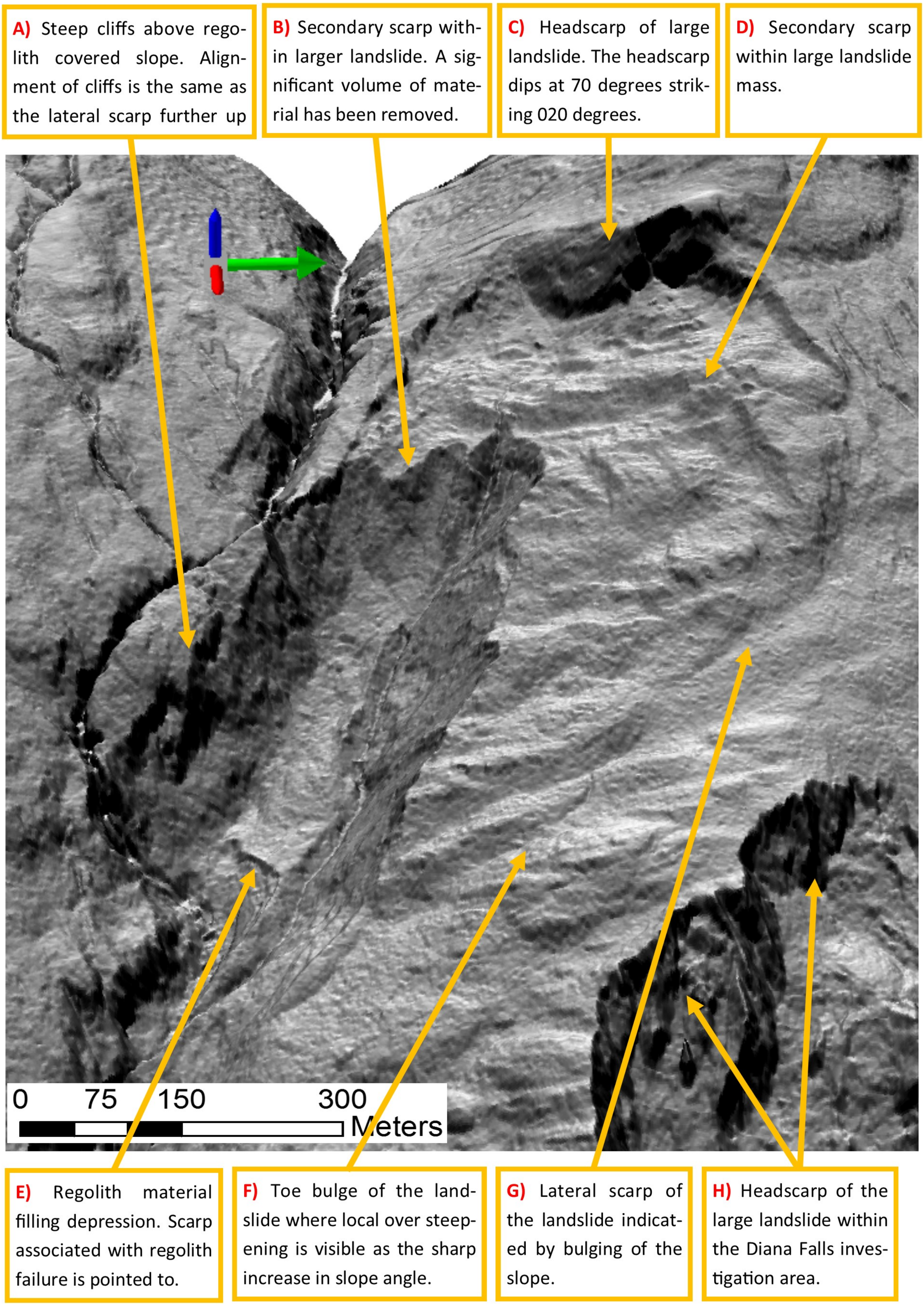

Figure 5.6: LiDAR slopeshade image of the Ford Creek landslide.

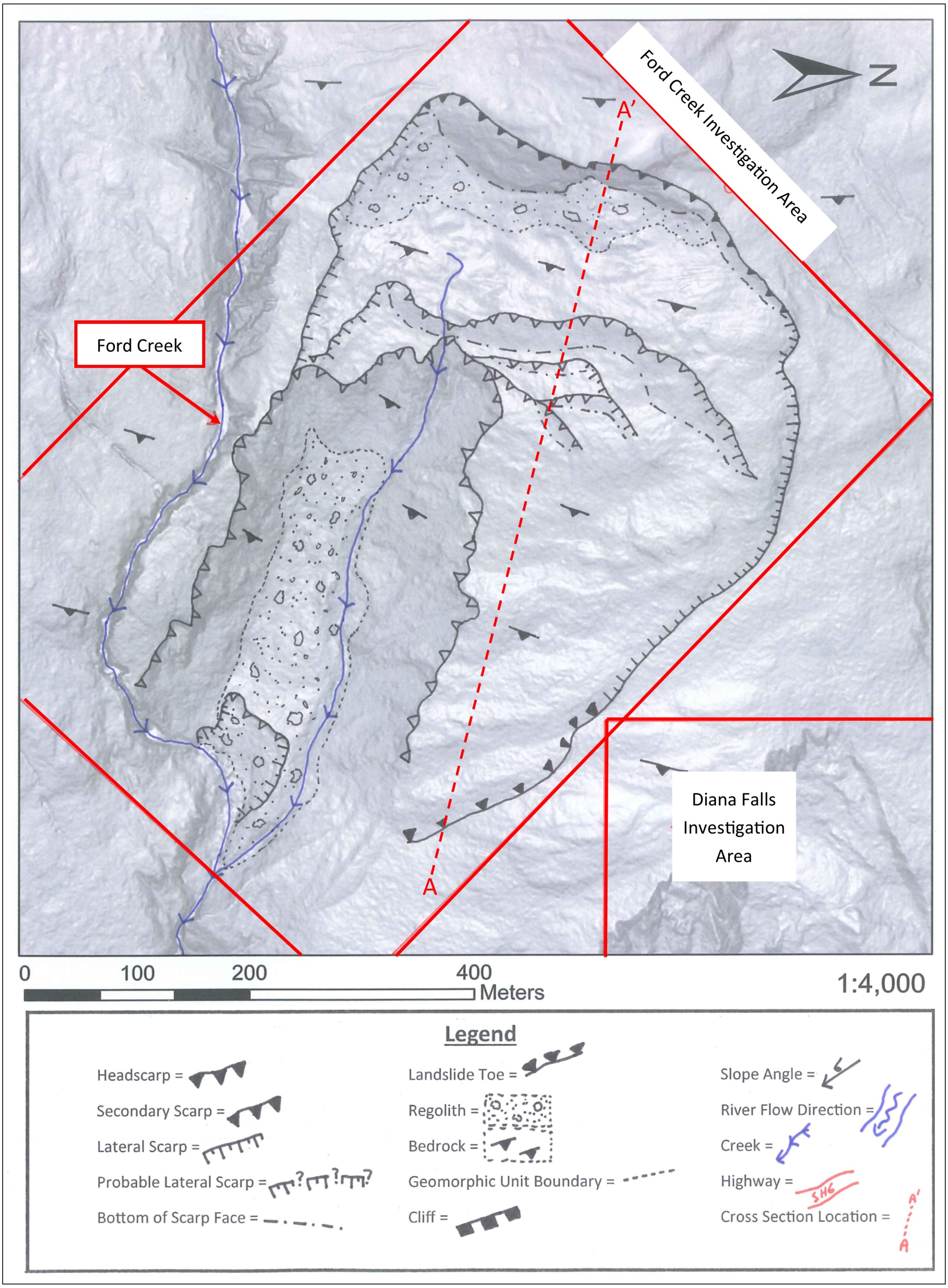

Figure 5.7: Engineering geomorphology map of the Ford Creek investigation area showing the distribution of bedrock, regolith materials and landslide features.

of the large landslide has failed along foliation defects as the surface of the cliff, striking approximately 020 degrees and dipping at about 70 degrees, follows regional bedrock foliation. On the northern and southern sides of the investigation area lateral scarps are clearly visible extending down from the headscarp with short steep bedrock cliffs marking the southern lateral scarp and a prominent surface undulation indicating the northern lateral scarp (Figure 5.6 G). The toe of the large landslide is identifiable on the northern side of the investigation area just above the large Diana Falls landslide Headscarp (Figure 5.6 F); Its appearance in the LiDAR surface is more subtle than the headscarp and lateral scarps , and can be identified by a sharp change in slope angle along undulations not parallel with the bedrock undulations. These features indicate that an area of bedrock of approximately 0.15km2 has been subjected to a deep seated mass movement in the past an may still be actively creeping. There is also evidence that secondary mass movements of bedrock within the main body has also occurred.

A number of secondary landslide features indicative of mass movement are visible within the main body of the Ford Creek landslide. The main body of the landslide has a surface texture that is more disturbed than the regular undulating textures observed on the rest of the slope indicating that the schist bedrock in this area has been subjected to internal deformations. Evidence of substantial deformation of the main landslide body is visible in the LiDAR surface as secondary scarps running across the slope. They appear as linear structures forming localised over steepening of the slope that are greater in magnitude than the normal undulations formed by bedrock anisotropy. The most visible secondary scarp forms the top of the large gully visible within the large landslide; the scarp has probably been formed by successive rockfalls and debris slides from the steep bedrock sides that have resulted in the loss of material from the slope and the build up of the regolith material at the base of the gully. Evidence of recent rockfall/debris slides from the sides of the gully are clearly visible in the aerial photo of the landslide in Figure 5.9 B and visible in the LiDAR surface as linear features forming steeper slopes indicated by the darker shading (Figure 5.6 D) with the locations of the secondary scarps, as indicated on the engineering geomorphology map in Figure 5.7. Within the regolith material located in the bottom of the gully a clear secondary scarp is visible at the base of the deposit where Ford Creek turns down slope (Figure 5.6 E). The aerial photo shows the secondary scarp and an exposure of the regolith material where recent landsliding has removed the vegetation and indicating that this feature is active.

5.3.4 Slope Subsurface Interpretation

The Ford Creek landslide appears to be a bedrock transnational planar slide with a deep-seated failure surface stepping along foliation and one other major defect. A schematic cross section through the slope is presented in Figure 5.8 indicates the nature of the subsurface as inferred from the LiDAR surface. The rockmass defects that facilitate the failure surface are less well understood at this site, however, their presence can be inferred from the surface expression of the landslide in the LiDAR surface. The main and most persistent defect within bedrock is foliation, however, another shallow defect, unable to be identified in the LiDAR surface, is required to facilitate failure. On a large scale the failure surface appears to be planar, however, at small scales the failure surface is likely to be stepped following foliation and a shallow dipping defect. The headscarp clearly visible as the cliff in the LiDAR surface is the headscarp of the landslide and given the cliff aspect and steepness represents the upper failure surface where extension and sliding along foliation planes resulted in the cliff formation. The toe of the landslide is visible as a linear features in the LiDAR surface and a local over steepening of the slope that is more apparent in the cross section. The toe of this landslide has resulted from compressive forces induced from the increased loading from movement of the material up slope.

5.3.5 Failure Modes

There are a number of potential failures modes that could be acting on the slope to produce the landslide expression seen in the LiDAR surface. The lack of subsurface information means that is it not possible to precisely identify the failure mode acting on the slope and instead there are a number of potential scenarios presented. They are listed below in order from most likely to least likely with comment about the reasons for the ranking indicated in the bullet pointed sections below.

1. **Rock Compound Slide**

    - The most likely mode of failure for the Ford Creek landslide is a complex rock compound slide. In this mode of failure the movement is accommodated through several rupture surfaces and considerable internal distortion of the main landslide body. In this mode the generation of many secondary scarps is common as a result of the internal deformations. This mode is the most realistic as it accounts for the presence of secondary scarps and distortion of the surface textures fits with rock compound slide behaviour.

2. **Rock Flexural Toppling**

    - The next potential failure mode would be rock flexural toppling that consists of forward rotation of rock out of the slope. This failure mode has been identified on other slopes in the area, however, the schist foliation attitude with respect to the slope is different. The persistent defect controlling failure would need to dip perpendicular to the fall line of the slope. Since schist foliation on the slopes above the highway dips steeply but in the same direction as the slope it is unlikely for flexural toppling to occur.

3. **Rock Transnational Planar Slide**

    - The final failure mode that could potentially result in mass movement of the Ford Creek Landslide is transnational planar sliding of the rock along a low angle defect. This failure mode is unlikely as a transnational planar slide is characterised by little to no internal deformation with the rockmass failing as a relatively intact mass. This is not the case at Ford Creek as considerable slope deformation is visible in the LiDAR surface within the main body of the landslide.

5.3.6 Present Slope Stability

The main problem with identifying the present state of stability of the landslide through remote sensing techniques is that the mode of failure results in slow progressive movements over time. This problem is compounded by the heavily vegetated nature of the slope as the most obvious areas to

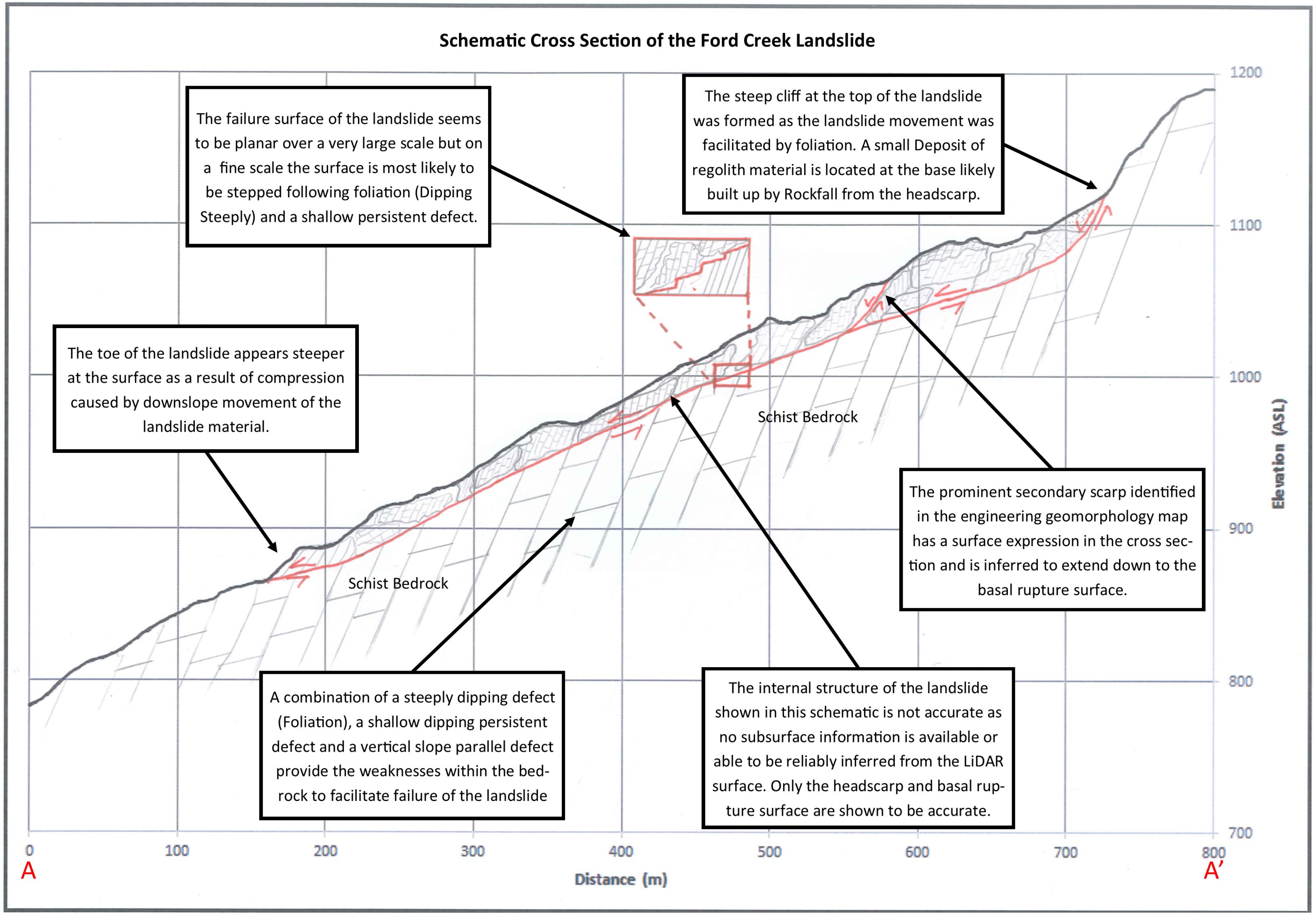

Figure 5.8: Schematic cross section through the Ford Creek landslide inferred from the LiDAR surface expression.

observe movement, at the toe and lateral scarps, is obscured. Therefore, it is not possible to evaluate whether the landslide is dormant or is still actively creeping down slope. There is, however, evidence of smaller and more recent secondary mass movements within the landslide. Visible in the aerial photo in Figure 5.9 is a recent rockfall/rockslide and a debris side. Both secondary mass movements are situated within the gully on the southern side of the landslide with the rockfall originating on the southern side of the gully (Figure 5.9 B). A recently active debris slide is visible at the base of the regolith material in the bottom of the gully where unconsolidated regolith materials have been exposed (Figure 5.9 C). Present activity that was able to be identified is confined to the walls and base of the gully with little evidence of larger scale mass movement, however this is not evidence of inactivity as if movement is occurring is is probably going to be very small in magnitude.

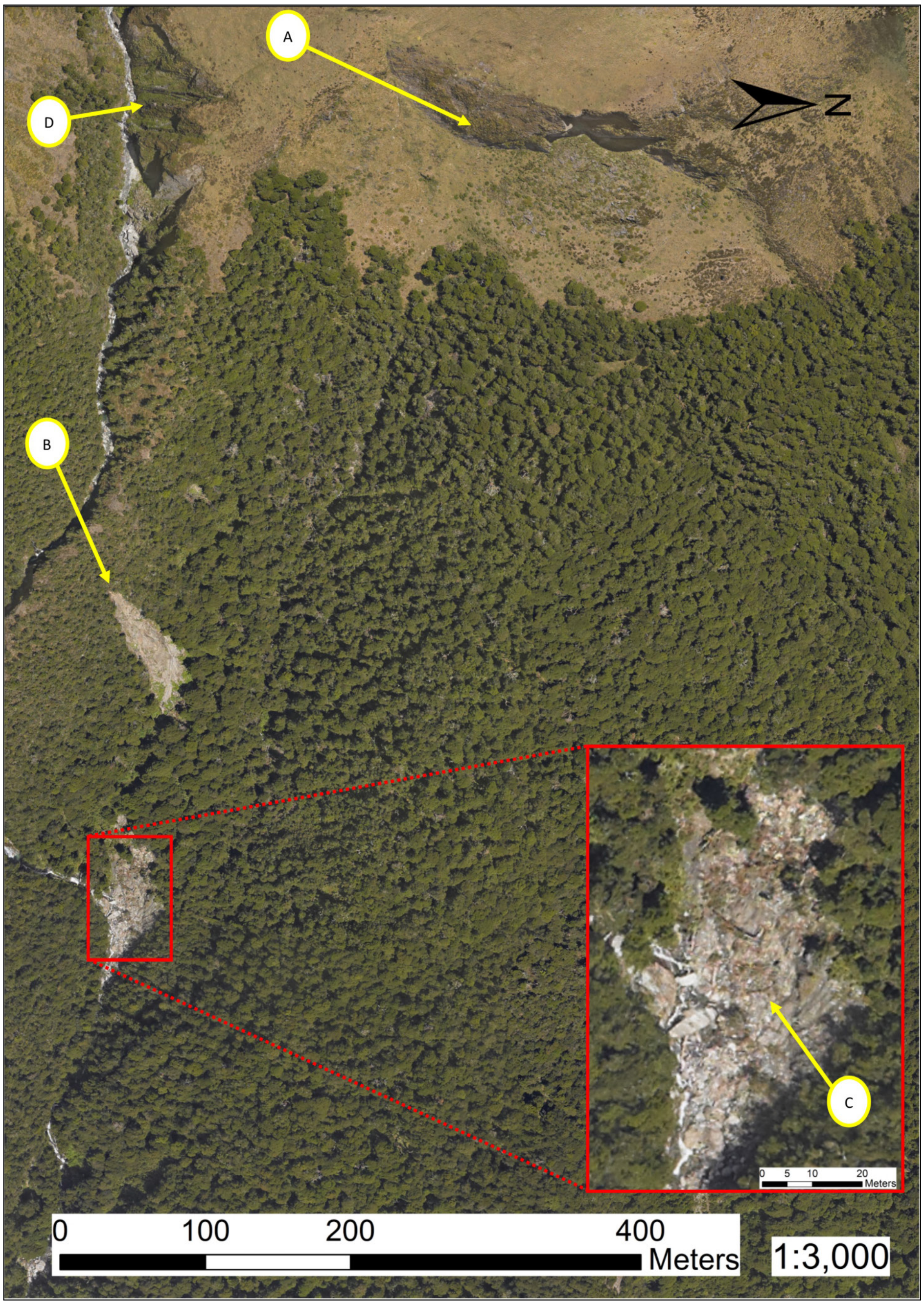

Figure 5.9: Aerial photo of the Ford Creek Landslide. A= Headscarp of the Ford Creek Landslide. B= Recent rockfall/rockslide from the side of a gully. C= Regolith materials exposed at the base of a gully by debris sliding action. D= Foliation lineations visible as well as another slope parallel defect set 20m east in the shaded region.

5.3.7 Future Slope Development

The future development of the Ford Creek landslide is uncertain as no monitoring has been undertaken and evidence of mass movement activity is limited to small localised failures of regolith and bedrock cliffs. Debris sliding of the regolith materials in the base of the gully will continue and the current scarp identified in Figure 5.9 C will continue to regress up slope. This loss of regolith material from the base of the gully is likely to promote rockfall and rockslides from the sides of the gully to contribute more material to the regolith body. The potential for further movement of the larger Ford Creek compound slide ultimately remains unknown as evidence of ongoing movement is not large enough to be detected by aerial photography. Until monitoring of the landslide and ground investigations are undertaken to try an observe evidence of recent or ongoing movement it is not possible to reliably evaluate the potential for further mass movements.

5.4 Detailed Evaluation of The Hinge

5.4.1 Site Overview

The Hinge investigation area consists of the slopes both above and below the highway within the area indicated in Figure 5.1 by the yellow box annotated The Hinge. The site was identified in Chapter 4 as consisting of a steep cliff with a steep regolith deposit between it and the river and the highway cutting through the middle of the deposit. The site was chosen for a more detailed investigation due to the potential hazard posed by the steep cliff, regolith deposit and the potential for mass movements due to the proximity of the river. Another reason for focusing on this site is that the site has been the subject of engineering reports in the past due to mass movements that have resulted in deformation of large sections of the roadway Opus (2001). A combination of LiDAR surface imagery and aerial photography are used to identify the geomorphic units, landslide features, and evaluate the current and future stability of the slope.

5.4.2 Surface Units

The dominant feature of The Hinge investigation area is the extensive steep cliff above the highway (Figure 5.10 A). The cliff itself ranges from 40 to 80 metres in height, has a slope face angle of between 65 and 75 degrees, and surface aspect of 095 to 100 degrees; Given the persistence of the cliff, the steep slope angle and the surface aspect of the cliff it represents an exposure of schist bedrock that has failed along foliation with a number of steps along other persistent defects particularly in the middle and southern parts of the investigation area. Above the cliff bedrock surfaces are widespread with small cliffs and persistent lineations indicating the presence of bedrock very near the surface (Figure 5.10 B). A number of small regolith deposits are located beneath some of the cliffs and tend to be small with very localised sources (Figure 5.10 C). The northern extent of the investigation area is composed of schist bedrock with cliffs, steep slopes with little regolith cover and exposures of schist bedrock next to the highway(Figure 5.10 D). The southern end of the investigation area appears to be covered with an extensive cover of regolith, but the presence four bedrock cliffs and an area of bare exposed bedrock further up slope suggests that regolith cover is thin in this area (Figure 5.10 E). The location and distribution of bedrock surfaces is indicated in the engineering geomorphology map in Figure 5.11.

Regolith cover is variable in thickness and extent within the investigation area, with the slope below the large cliff consisting of the largest deposits (Distribution mapped in Figure 5.11). The southern end of the slope beneath the large bedrock cliff consists of widespread regolith cover extending from the base to the steep bedrock cliff down to a bedrock area next to the highway (Figure 5.10 F). The slope below the highway in the southern end of the investigation area is covered by regolith that extends from the highway down to the river (Figure 5.10 G) with steeper slopes that are likely isolated rock masses that could be bedrock or displaced boulders (Figure 5.10 H). In the middle of the investigation area the cliff approaches very close to the highway with only relatively small deposits of regolith present between it and the highway. Below the highway in this area regolith material covers nearly the entire slope with only small cliffs indicating the presence of isolated rock masses. The northern section of the investigation area where the cliff extends away from the highway is where the most extensive cover of regolith material is present. Rough undulating textures indicative of regolith cover extend across the entire slope between the large bedrock cliff and the river with no indication of large rock masses within (Figure 5.10 I). Given the very small deposits of regolith material on the slope above the large cliff and the very large amount beneath it, it is most likely that the majority of regolith material below the cliff is sourced from rockfall or rock slides from the cliff itself.

5.4.3 Landslide Features

There is evidence in the LiDAR surface that indicate bedrock and regolith within The Hinge investigation area have been subjected to mass movement activity. Within the investigation area many of the bedrock areas consist of steep cliffs visible in the LiDAR image in Figure 5.10 as the very dark areas of the slopeshade image. These cliffs are formed by rockfall and rock sliding of schist rock as it fails along rockmass defects, most notably schist foliation and one more persistent rockmass joint. Evidence of failure along rockmass defects is indicated by the preferential orientation of most of the cliffs in the investigation are with most cliff faces aligned along foliation, striking 020 and dipping at around 70, and another persistent defect within the rockmass, striking approximately 110 and dipping steeply. It is failure of bedrock from the areas surrounding the regolith deposit, most likely through rockfall and rock sliding, that has resulted in the formation of the regolith deposit currently located below the cliff.

There are features in the LiDAR surface that indicate secondary mass movements of the regolith material below the cliff has occurred. While the regolith material in the LiDAR surface appears very rough and irregular in appearance there are stepped features in the slope that are more persistent and larger in magnitude than the normal undulations of the regolith surface. The stepped and persistent slope breaks are inferred to be secondary scarps, formed as a result of remobilisation of the regolith material due to parts of the deposit moving down slope through debris sliding/debris creep processes. Nearly all the slopes below the highway in the investigation area contain secondary scarps with headscarps just below the highway and lateral scarps extending down slope to the river (Figure 5.10 J). In the southern half of the regolith deposit the slopes above the highway do not show clear indications of secondary scarps but the presence of regolith material indicates past rockfalls and secondary mass movements are likely to still be occurring but are to small to be detected. In the northern half of the investigation area below the bedrock cliff, a clear secondary scarp is visible extending from just beneath the bedrock cliff and extending down slope to cross the highway and down the slopes below the highway to the river (Figure 5.10 J). There is also another large secondary scarp present within the main secondary scarp and two smaller scarps on the slope just above the river (Figure 5.10 J). The LiDAR surface shows that nearly all slopes below the highway and the slopes above the highway in the north of the investigation area have been subjected to secondary remobilisation of the regolith deposit on the slope below the cliff. The location of these scarps in relation to one another is shown in the engineering geomorphology map in Figure 5.11.

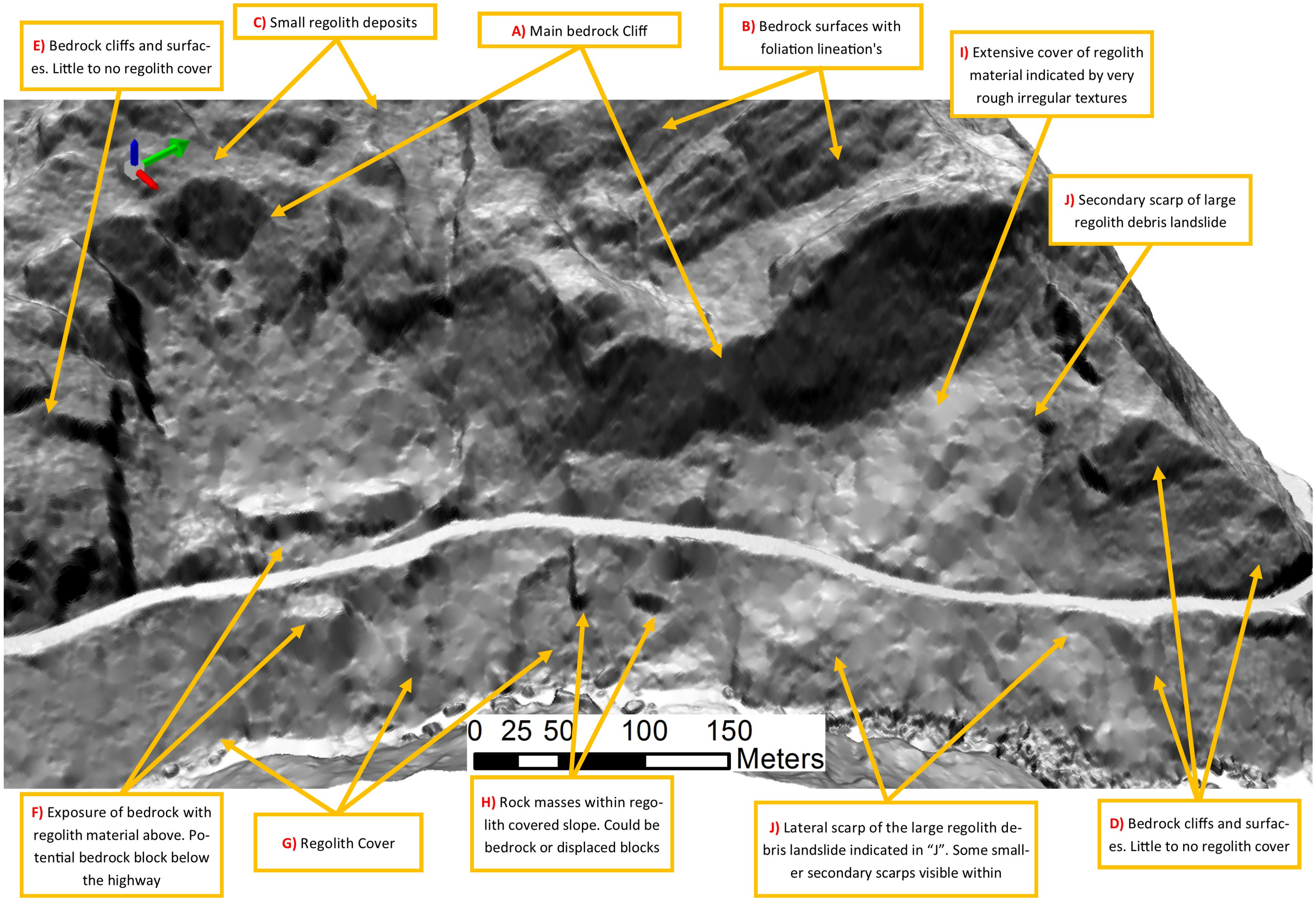

Figure 5.10: LiDAR slopeshade image of The Hinge investigation area.

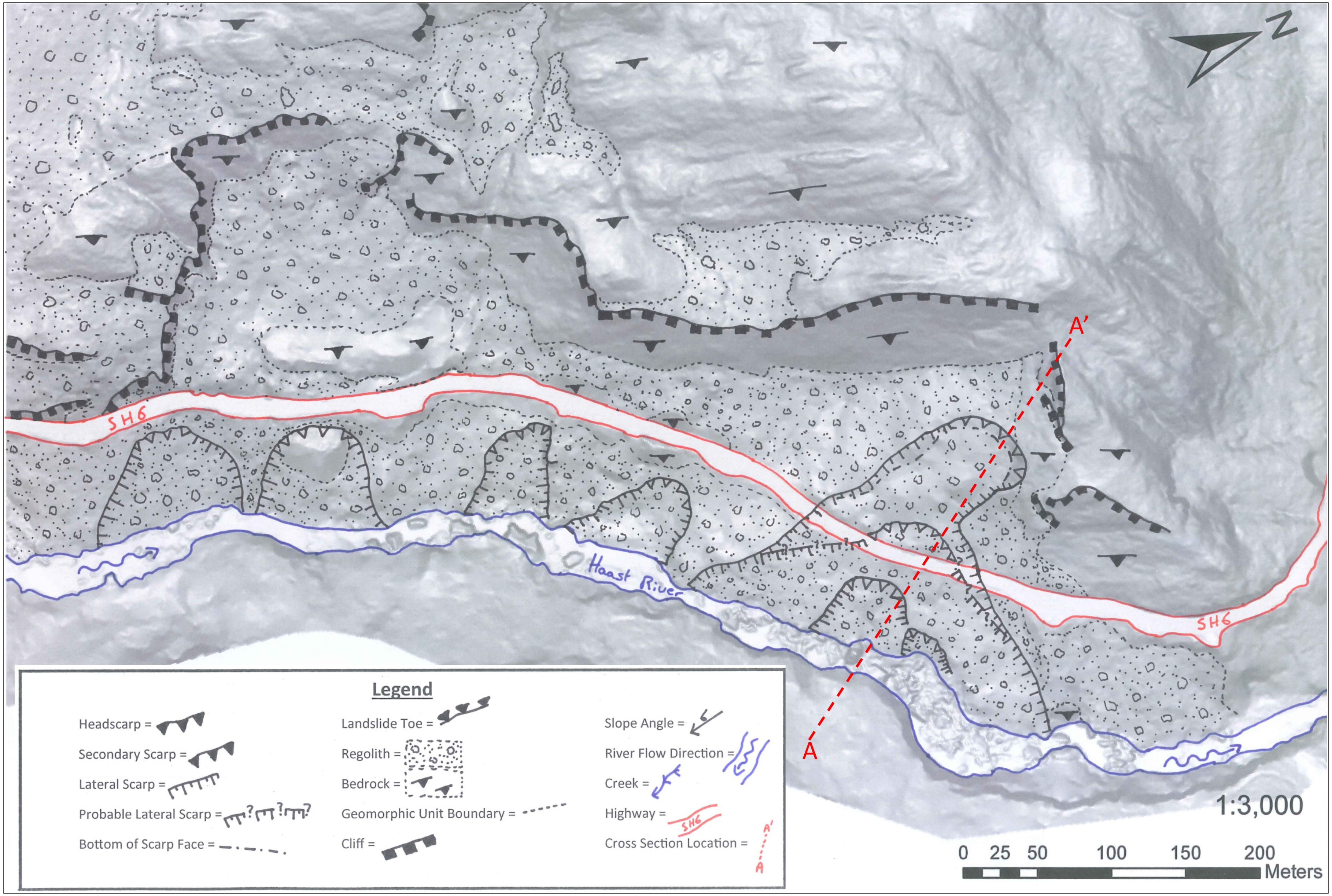

Figure 5.11: Engineering geomorphology map of The Hinge investigation area showing the distribution of bedrock, regolith materials and landslide features.

5.4.4 Slope Subsurface Interpretation

It is possible to make a reasonable evaluation of the thickness of regolith materials at The Hinge based on the overall slope morphology visible in the LiDAR surface in Figure 5.10. While it is not possible to determine the exact depth of regolith materials from the LiDAR surface, it is possible to make a reasonable interpretation based on the overall bedrock morphology of the cliff and areas above. Based on bedrock morphology it is apparent that a reasonable thickness of regolith in the range of tens of metres rather than a few metres of regolith material is present in the northern part of the investigation area; The thickness of regolith material in the middle and southern section of the site appears to be thinner than the northern section with the presence of rock masses inferred to be bedrock suggesting this. Overall regolith thickness varies across the investigation area with the thickest deposits located in the northern end of the investigation area; thinner deposits are located in the middle section and above the highway in the southern part of the investigation area with the areas below the highway in the southern end observed to have a reasonable thickness of regolith cover.

A cross section through the regolith material in the northern part of the investigation area is shown in Figure 5.12 providing an interpretation of the subsurface profile based on the overall slope morphology. This section of the slope was selected as the site for the cross section as it had clear signs of remobilisation of regolith materials in the LiDAR surface and was subjected to mass movements in the early 2000's (Opus 2001). The bedrock-regolith interface is indicated on the cross section and is only speculation as to the depth of the surface based on the surround bedrock morphology. The uppermost scarp in the regolith deposit visible in the LiDAR surface is indicative of large scale mass movement and given the size and persistence of the lateral scarps, is likely to extend deep into the regolith deposit. A smaller secondary scarp was identified within the larger landslide scarp in the LiDAR surface and corresponds with a step in the slope surface. This feature was identified in an engineering investigation following subsidence of the highway and was found to show signs of recent movement (Opus 2001); It represents a secondary landslide within the main landslide body that is likely failing along the bedrock regolith interface or a shear surface within the regolith materials. Movements of this material is likely to be strongly influence by removal of the material at the toe of the slope by the river and by heavy rainfall, as was experienced before the landslide movements in the early 2000's (Opus 2001).

5.4.5 landslide Processes

Three distinct landslide processes have been identified acting on the slopes within The Hinge investigation area. The lack of subsurface information and extensive ground investigation means that only broad interpretations as to failure modes can be made using the LiDAR surface. The failure modes listed below outline the large scale processes acting on the bedrock and regolith deposits based on observations made of the LiDAR surface, subsurface interpretation, and previous engineering investigations.

1. **Rockfall**
    - The bedrock areas surrounding the regolith deposits and mapped in Figure 5.11 have been subjected to rockfall events in the past. The regolith material mapped covering

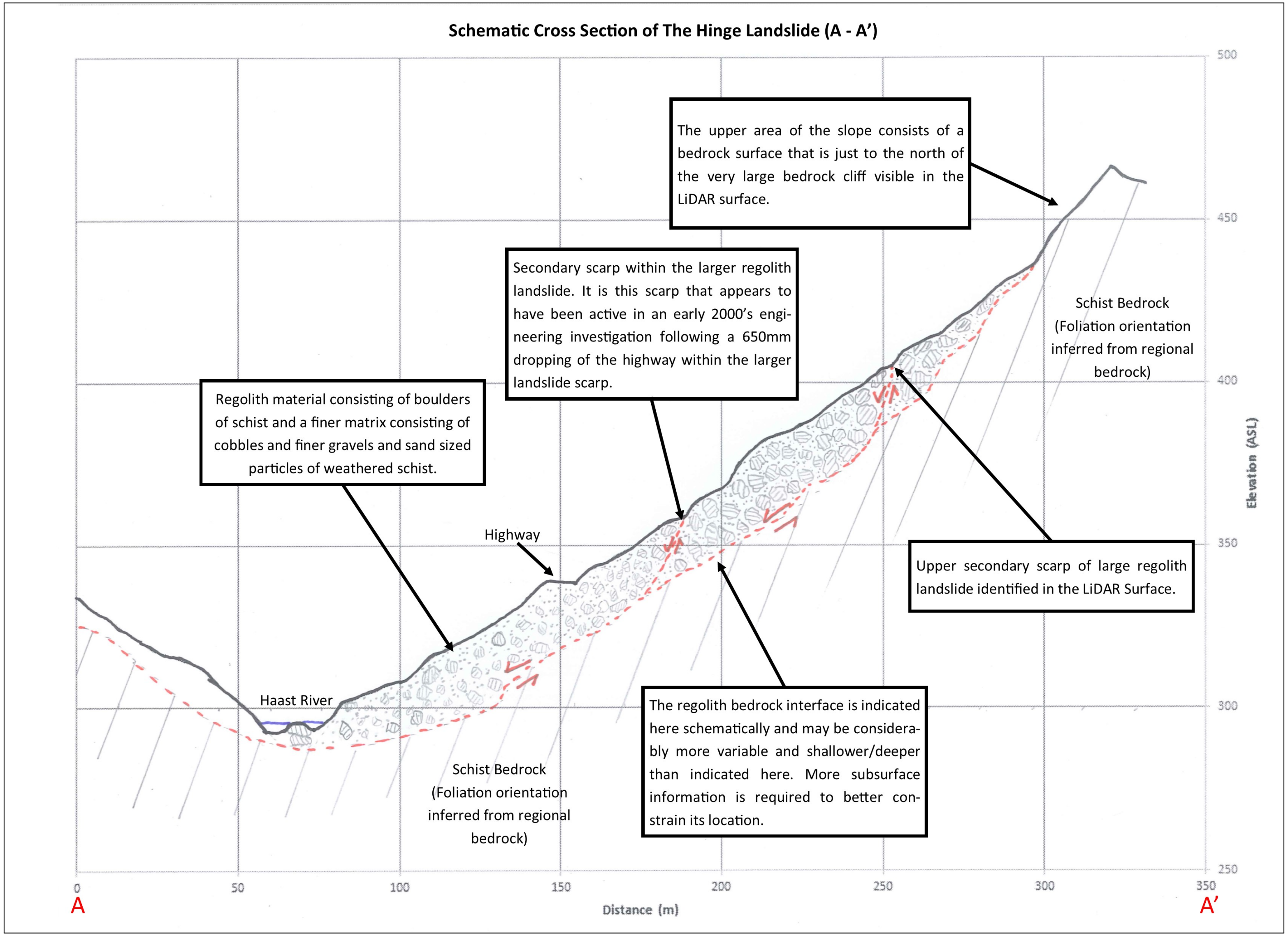

Figure 5.12: Schematic cross section through The Hinge inferred from the LiDAR surface expression. The location of this cross section is indicated by the A - A’ line in Figure 5.11

most of the mapping area below the steep bedrock cliff originates from the cliff above and has probably been built up by successive rockfall events. Removal of regolith material will contribute to the destabilisation of the large bedrock cliff and increases the probability of failure. The trigger is unknown at this time as is the overall condition of the rockmass but if the rockmass is sufficiently jointed it is possible the heavy rainfall, loss of support from regolith material or/and earthquake shaking could result in a rockfall event.

2. **Creeping Debris Slide**

   - Creeping debris slides consist of the slow movement of regolith materials, in this case regolith consisting of schist boulders in a finer matrix of finer material, sliding along a failure surface either within the regolith material or along the bedrock-regolith interface. Evidence of this processes was identified in the LiDAR surface and recent activity has been recorded in engineering investigations. It appears that debris creeping processes are active within the landslide scarp identified in the northern end of the investigation area and this activity probably extends to many of the scarps below the highway. The creeping debris slide is likely triggered by heavy rainfall in combination with removal of material from the toe of the landslide by the Haast River.

3. **Rapid Debris Slide**

   - Continued creeping debris slides could lead to more rapid failure od the regolith material if particularly heavy rainfall and loss of material of the toe were to be sustained. A transition from creeping to rapid debris slide behaviour would occur as acceleration of slope movements before a very rapid acceleration towards total failure.

5.4.6 Present Slope Stability

Evidence from both engineering reports (Opus 2001) and aerial photography indicate that several areas of The Hinge investigation area are subjected to ongoing mass movement activity. Fresh exposures of regolith material are visible at the base of some slopes below the highway where it appears a combination of river scour and landsliding has removed vegetation cover (Figure 5.13 A). Outside of the areas showing very recent mass movement activity there are variations in vegetation age across the rest of the slopes below the highway. These variations are likely a result of vegetation regrowth after debris slides with the areas of very young vegetation that appear as the brighter green areas in Figure 5.13 having been subjected to debris sliding more recently. The only area that appears to be active above the highway is the debris slide in the northern end of the regolith deposit within the large landslide scarps. The highway at this location was subjected to 650mm of vertical displacement in December 2000 and has been subjected to continued but lower magnitude deformations in the years since (E. Stevens, personal communication, April 21, 2014). Unfortunately, it was not possible to identify any recent landslide movement features from the aerial photo due to the very dense vegetation above the highway, however, the extent of the slumping of the highway is located within the confines of the larger regolith landslide identified in the LiDAR surface. The areas that are currently showing signs instability and mass movement appear to be confined to the slopes below the highway as well as the landslide in the northern end of the regolith deposit above the highway.

5.4.7 Future Slope Development

It is almost certain that further landslide events will occur within The Hinge investigation area particularly within the regolith material beneath the large bedrock cliff. Ultimately river incision is driving slope instability over long time scales, with the river progressively lowering its base level and eroding material from the river bed and margins. River incision will persist into the future resulting in a lowering of the river bed and further erosion of material from the base of the regolith deposit. Loss of material from the toe of the slope has resulted in debris sliding of the regolith covered slopes below the highway and will continue to do so into the future as long as material continues to be removed. In the middle and southern parts of the investigation area the cover of regolith material appears to be thinner than in the north with large rock outcrops indicating the presence of bedrock as shallow depths. The presence of bedrock in these areas is likely to reduce the impact that regolith debris slides below the highway have since failure of regolith material is unlikely to include bedrock. The larger thickness of regolith material in the north will cause problems for the highway in the future as material lost from the lower slopes increases the possibility of the reactivation of the large debris slide extending above the highway. Continued loss of regolith material from the base of the cliff will have an effect on it overall stability but without knowing the current state of the rockmass it is not possible to evaluate whether rockfall from the cliff is likely in the short to medium term. Over long time scales it is certain that continued river incision will eventually result in further rockfall events., but It is the slopes below the highway and particularly the thicker regolith deposit in the north of the investigation area that will to experience further mass movement events in the short to medium term.

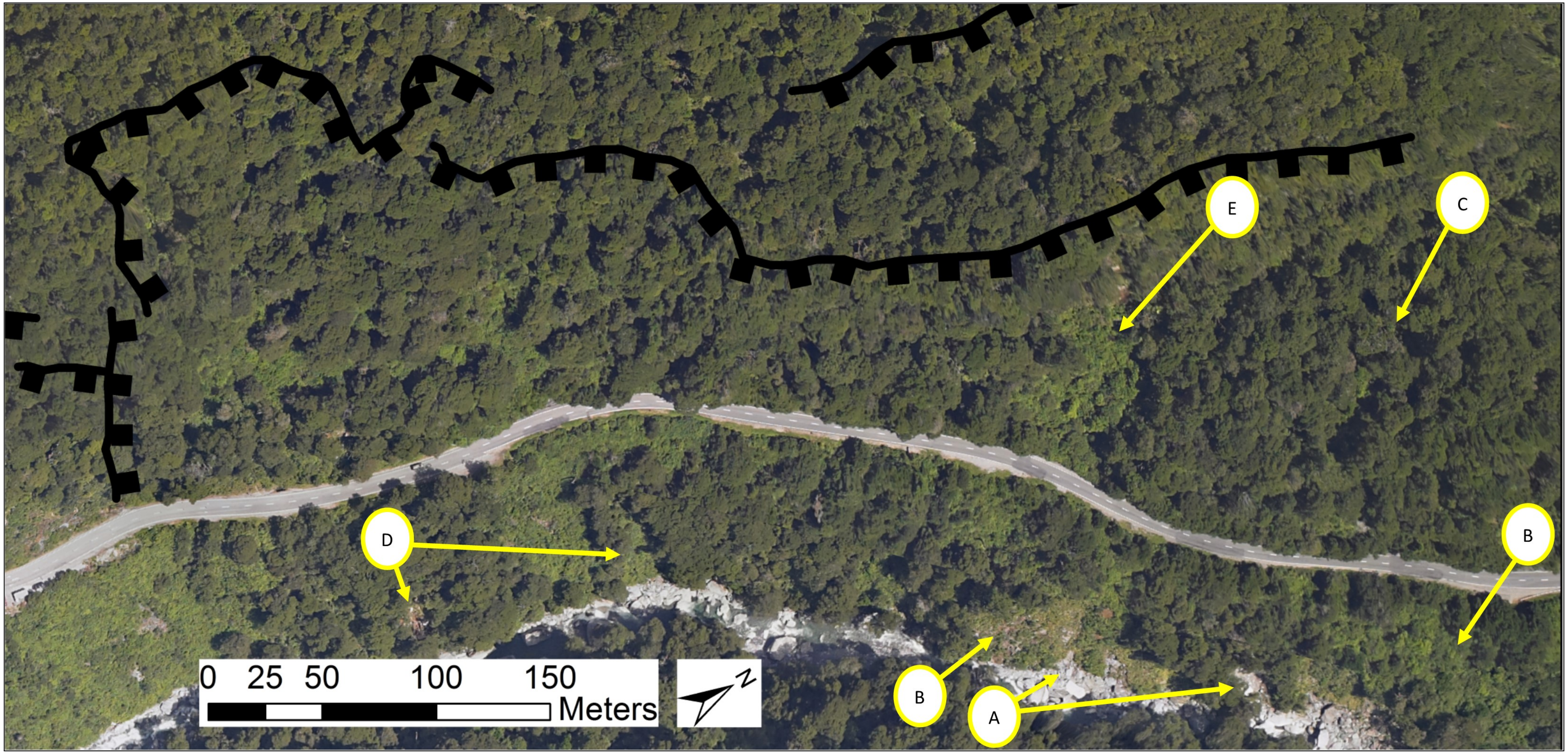

Figure 5.13: Aerial photo of The Hinge. A) Exposure of regolith materials as a result of slope failures caused by river erosion. B) Location of the lateral scarps identified in the LiDAR surface with corresponding breaks in the vegetation likely caused by loss of vegetation due to landsliding. C) Location of the headscarp of the large regolith debris slide identified in the LiDAR surface. D) Small failures of regolith material below the highway indicated the an area of young vegetation and a visible landslide with regolith material exposed. E) Young vegetation likely indicating past landslide activity at this location.

5.5 Detailed Evaluation of the Gates of Haast

5.5.1 Site Overview

The Gates of Haast investigation area consists of the slopes above the highway in the vicinity of the Gates of Haast bridge and extends from river level to the crest of the slope. The full extent of the investigation area is shown in Figure 5.1 as the yellow box annotated as the Gates of Haast investigation area. The site was chosen due to the long history of instability recorded since the highways construction, insights into the areas previously proposed for a new bridge and the new information that the high resolution LiDAR survey can shed on the overall context of the previously identified landslides. A combination of LiDAR imagery, aerial photography and subsurface records from previous engineering investigations are combined to give the most complete picture of this site to date.

5.5.2 Surface Units

Bedrock dominates the surface of the upper slope as well as the eastern and western sides of the mid slope with only isolated areas of the lower slopes consisting of bedrock. The upper parts of the slope are almost entirely composed of schist bedrock surface with very small deposits of regolith material in isolated gullies. The upper slope bedrock surfaces are predominantly made up of cliffs that strike slope parallel aligned with regional schist foliation and steep slopes with some covered by small regolith deposits (Figure 5.14 A). On the mid slope large bedrock areas are located to the east and west of a large regolith deposit occupying the middle of the investigation area. The bedrock areas on the mid slope mostly consist of steep bedrock slopes with cliffs that are less numerous than on upper slopes. Overall slope angles are gentler as indicated by the lighter shading visible in Figure 5.14. The lower portion of the slope both above below the highway is dominated by regolith deposits. Isolated ridges of bedrock extend down from the mid slope extending down to the highway but do not appear to be visible below the highway (Figure 5.14 B). An isolated area of what appears to be bedrock is located below the highway just offset from the eastern most ridge but it is not clear if it connects with the ridge (Figure 5.14 C). The map in Figure 5.15 shows to full extent of bedrock within the investigation area.

Regolith cover is generally confined to the lower slopes where extensive and thick deposits are present with some small and thin deposits located on upper slopes. Regolith on the upper areas of the slope is limited to small deposits below cliff and some small accumulations at the bottom of some gullies. The only extensive cover of regolith is located on the western side of the upper slope where a very thin cover of regolith material sourced from rockfall/slide is present (Figure 5.14 D). On the mid slope the centre of the investigation area consists of an extensive, and based on surface morphology of the deposit and surrounding bedrock areas, thick deposit of regolith confined between two predominantly bedrock areas (Figure 5.14 E). On the lower part of the slope from just above the highway to river level three distinct deposits are visible. The first situated, at the western extent of the investigation area, consists of a relatively small 100 metre wide deposit of regolith surrounded by bedrock that extends down to river level alongside the ridges identified previously (Figure 5.14 F). East of this small deposit the largest regolith deposit extending from the large landslide scarp near the top of the slope down to river level is present with the highway cutting across the approximately 200 metre wide deposit (Figure 5.14 G). The eastern most deposit of regolith material on the lower slope is situated just upstream of the highway bridge and consists of regolith sourced from the steep bedrock cliffs above (figure 5.14 H). From the LiDAR surface it is clear that the highway crosses mostly regolith material sourced from landslides form the bedrock areas above. The full extent of regolith materials within the investigation is shown on the map in Figure 5.15.

5.5.3 Landslide Features

Evidence of widespread landsliding is visible in the LiDAR surface on bedrock slopes as well as within some regolith deposits. The most extensive landslide features are the numerous cliffs that are found in all the bedrock areas and are identified by the dark shaded regions of the slope shade image in Figure 5.14. The presence of so many cliffs on the slopes, particularly on the eastern upper slope, indicates that large areas of slope composed of bedrock are susceptible to landslide activity. Evidence of large scale landslide activity is the presence of a large scarp on the upper slope, visible in the LiDAR surface as the very dark area in the middle of the upper slope (Figure 5.14 I). The scarp face stands almost 40 metres tall with regolith material filling the area inside the scarp. The scarp is located at the head ward extent of the thickest deposit of regolith material and has contributed a significant quantity of material to the deposit, either suddenly during one large event or gradually through rockfall/slides and debris flows. Identification of landslide features within the regolith materials is difficult as extremely dense vegetation dramatically reduces the resolution of the LiDAR surface. Any landslide features that area present are likely to be too small in size to be detected given the nature of the surface expression as a result of slow creeping debris slides.

5.5.4 Slope Subsurface Interpretation

The slope subsurface of the Gates of Haast investigation area is made up of a mix of schist bedrock as well as landslide and fluvial derived regolith deposits. The cross section through the slope, in Figure 5.16, shows the interpretation of the thickness and location of these materials. Above the large bedrock scarp identified in the LiDAR surface the slopes consists entirely of schist bedrock with very minor deposits of regolith materials. Below the large bedrock scarp the slope surface is covered by landslide derived regolith materials sourced from the bedrock slopes above The thickness of the regolith material on mid to upper slope, indicated on the cross section, is inferred from the LiDAR surface morphology rather than any subsurface data. The actual thickness may vary but based on the LiDAR surface morphology a significantly thick deposit is present. On the lower portion of the slope, in the area between the top of the zig-zag track and river level, previous engineering investigations provide more accurate information on the composition and thicknesses of the various subsurface units. Two distinct units are identified within the borehole logs from the 2002 investigation of the Gates of Haast Landslide (Opus 2001). They reveal that the upper unit consists of landslide derived regolith materials with grey colour angular sands, gravels and boulders while the lower unit consists of alluvium containing brown sub-angular to sub-rounded silts, sands and gravels some of which display weak bedding (Opus 2001). The 2002 investigation of a creeping debris slide above the highway mapped the headscarp of the failure and a flat area that corresponds

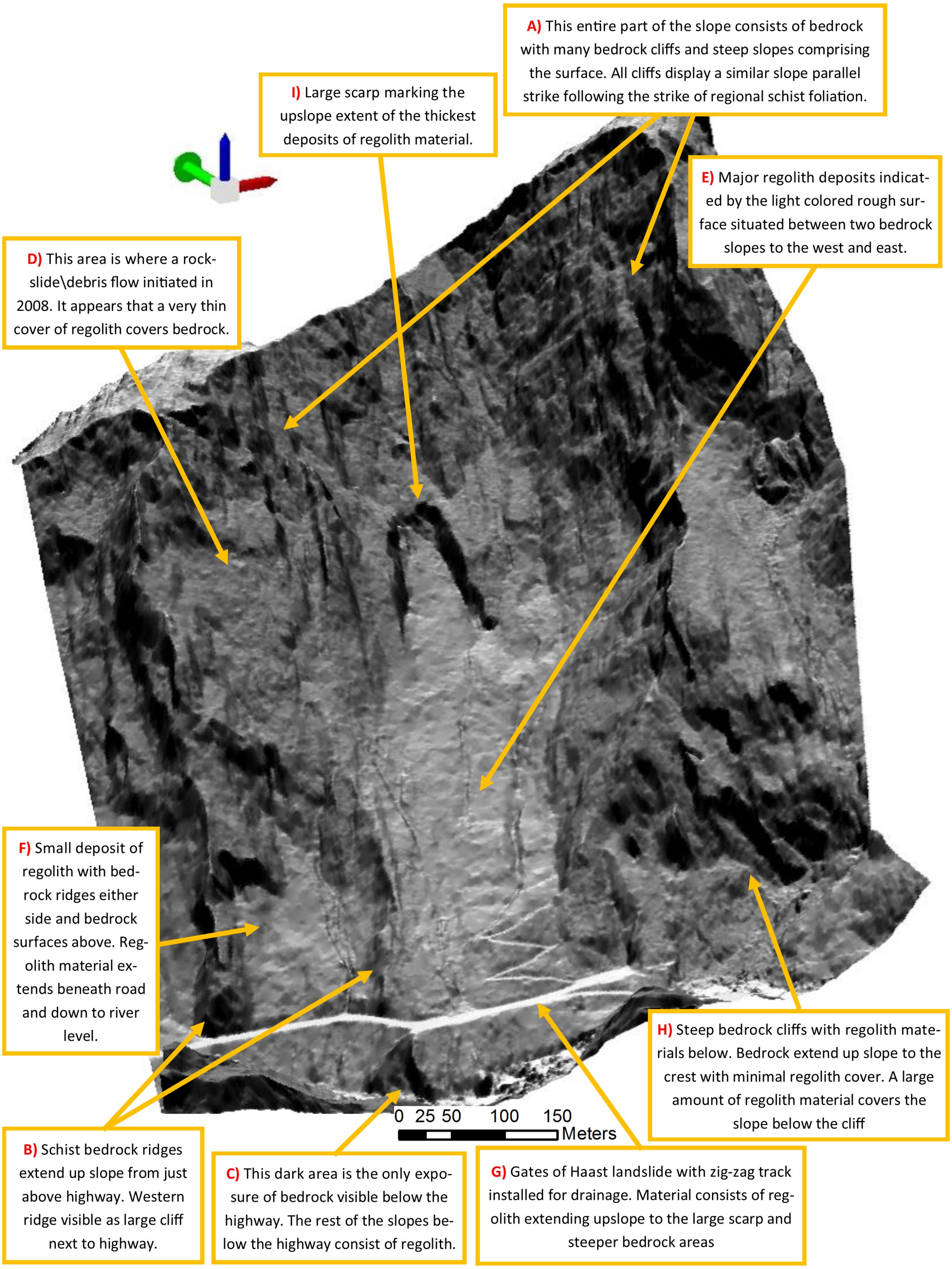

Figure 5.14: LiDAR slopeshade image of The Gates of Haast investigation area.

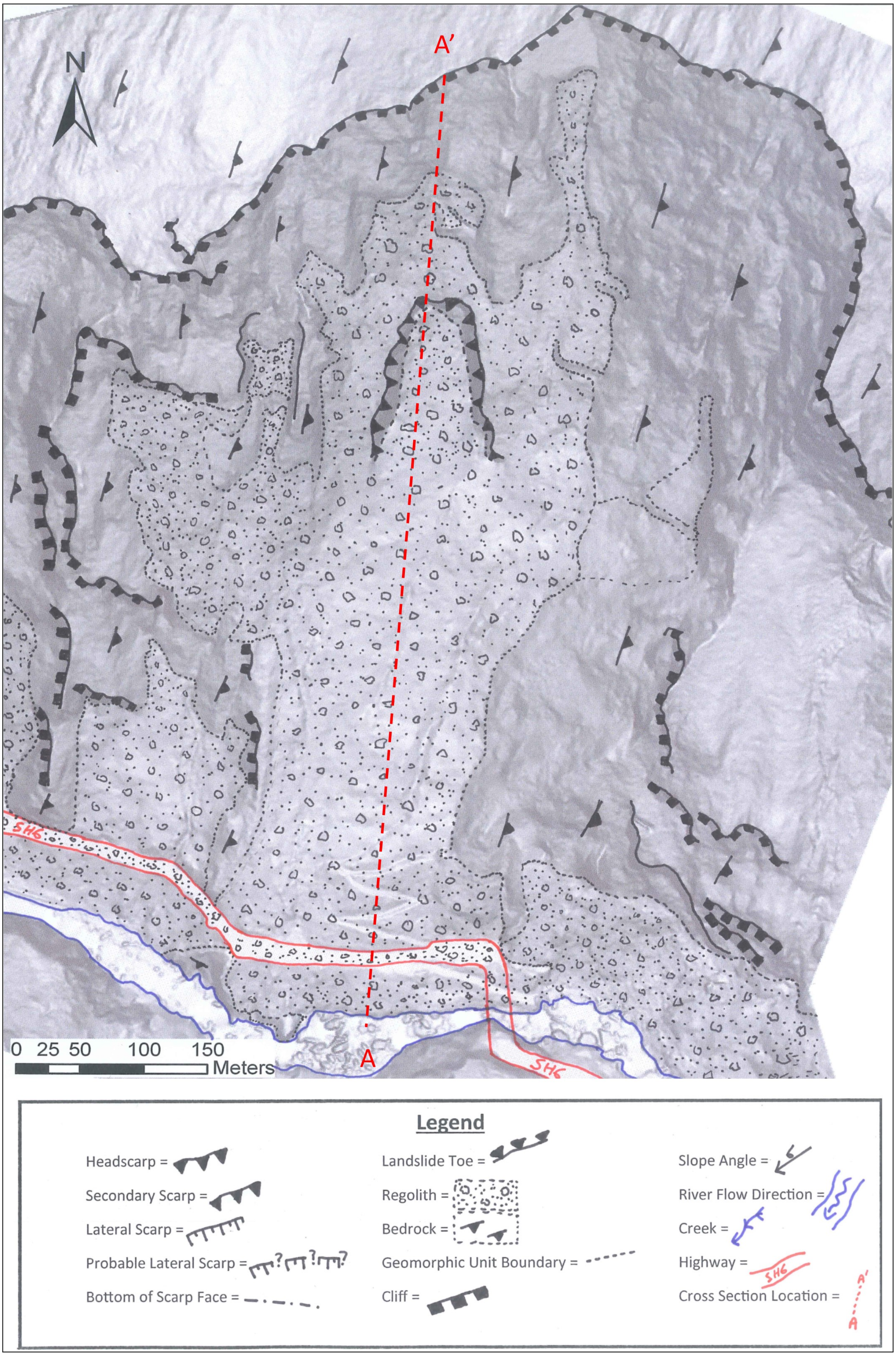

Figure 5.15: Engineering geomorphology map of the Gates of Haast investigation area showing the distribution of bedrock, regolith materials and landslide features.

with the approximate location of the headscarp is visible in the cross section in Figure 5.16. While landslide derived regolith material was expected to cover the lower slope, the presence of alluvial material is surprising.

Identifying the origins of the landslide derived regolith material is relatively straightforward, however the origins of the alluvial material beneath the landslide regolith is more complex and difficult question to answer. The regolith cover on the upper slopes is largely deposited through landsliding from the steep bedrock areas surrounding it, where rockfall, rocksliding and debris sliding processes dominate this part of the slope with material driven solely predominantly by gravity. On the mid to lower slopes the processes transporting the regolith material also involve water as debris sliding and debris flows dominate transport processes. There is the potential that the large landslide scarp at the top of the regolith deposit represents a large and sudden failure that could have deposited a significant amounts of material instantaneously. Currently, there is little evidence confirming this scenario other than some brief references to a soil horizon with rootlets in an early investigation for the northern bridge abutment. The presence of the alluvial material beneath the regolith deposit on the lower slopes is a problem as the current character of the valley is not suitable for accumulations of alluvial material even if the regolith deposit was absent. With only limited information on the location, composition and lateral extent of the alluvial material in a handful of bore logs it is only possible to speculate as to its origins. It is possible that it represents the material that filled the valley before uplift on the eastern side of the alpine fault resulted in down cutting of the river through the deposited alluvium. The down cutting of the river and uplift would have also lead to instability of the valley sides that would result in deposition of regolith material on the valley bottom.

5.5.5 Landslide Processes

Four major landslide processes have been identified acting on the slope above the highway within the Gates of Haast investigation area. Analysis of the LiDAR surface, aerial photography and previous investigations at the site reveal that nearly the entire slope is potentially capable of being a source of one or more landslide types. The landslide processes as well as the areas affected and potential causes of the instability are indicated in the bullet pointed list below.

1. **Rockfall**

    - Rockfall from the steep bedrock cliffs within the investigation area, particularly the eastern upper slope, appear to be susceptible to rockfall events. A combination of foliation, a defect forming the east west striking cliffs and one other unidentified defect are probably the discontinututies resulting the formation of schist blocks that are then able to fall out of place; The trigger for these rockfall events is unknown as they have not been observed in this study.

2. **Rock Slide**

    - Rock slide eventsS occur where where bedrock surfaces dip down slope shallowly enough to induce sliding rather than falling with blocks formed by a combination of rockmass defects. A number of these planar surfaces are visible on the upper slope particularly on the western half of the investigation area. A 2008 landslide above the small regolith

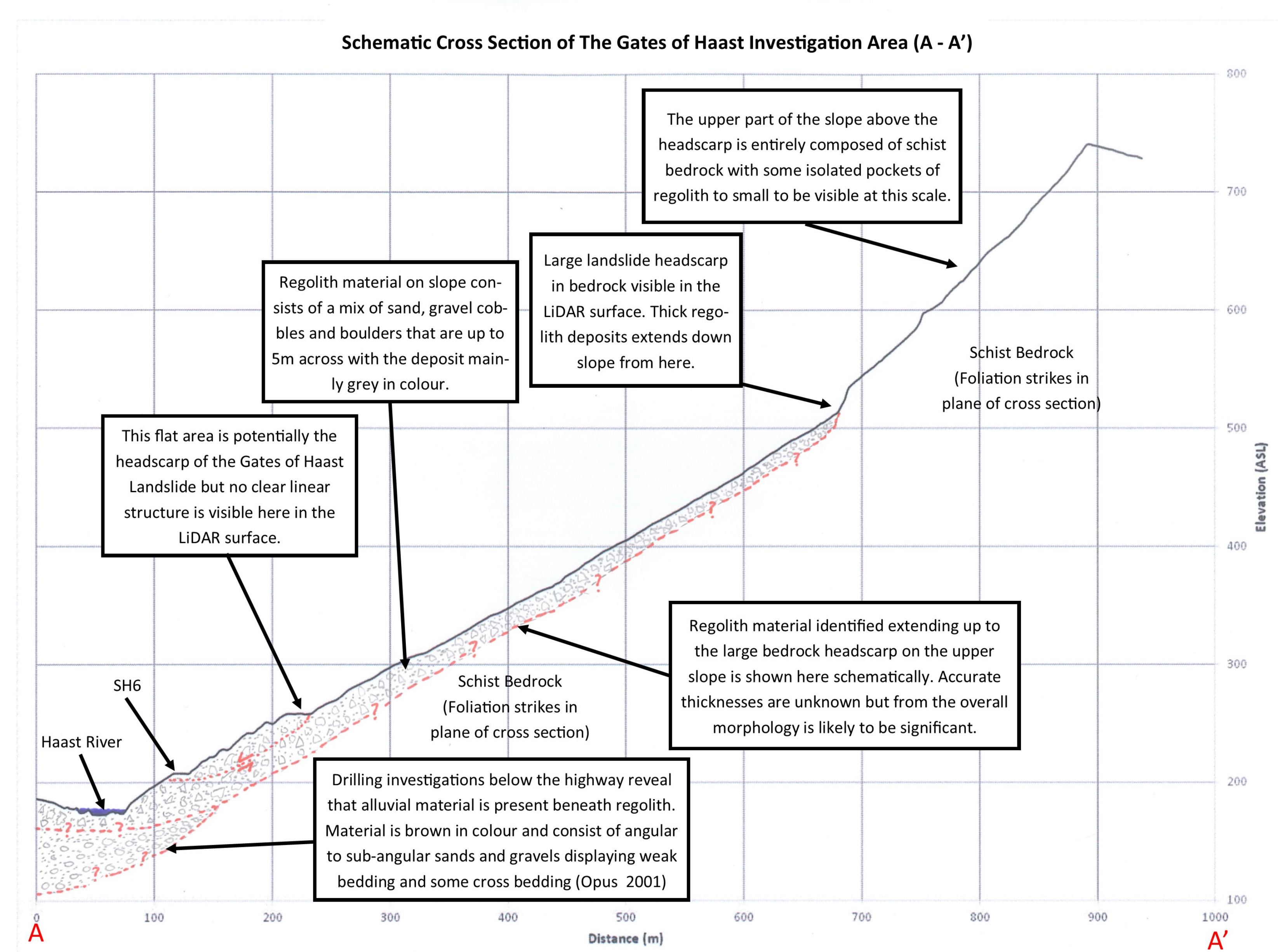

Figure 5.16: The Gates of Haast Investigation area cross section

deposit on the western side appears to be a rocksliding event based on observations of the failure surface visible in the aerial photo in Figure 5.17 A.

3. **Debris Slide**

    - Debris sliding has been recognised as occurring within the regolith material covering the slope with recent small shallow failures visible in the aerial photo and the larger deep seated failure next to the highway at the Gates of Haast recorded in engineering reports. The regolith deposits on the slope are susceptible to debris slides as a result of the very steep slope angle and the high rainfall that the area receives. Recently, this instability appears to have resulted in small low displacement failures with evidence from around highway level that the larger debris slide at the Gates of Haast may be continuing to creep.

4. **Debris Flow**

    - Older aerial photos and engineering reports from the 70's and 80's mention that debris flow activity within the large regolith deposit was common. The large regolith deposit in the centre of the investigation is completely covered by thick vegetation in the most recent aerial photo in Figure 5.17 B, but the aerial photo in Appendix E shows large areas of the slope subjected to debris flow activity with little vegetation cover. While a debris flow was recorded at the regolith deposit to the west this appears to have resulted from rocksliding/debris sliding on the upper slope that developed into a debris flow.

5.5.6 Present Slope Stability

The evidence of continued instability on the slopes within the investigation area is clearly visible in the 2014 air photo of the area and in the 1992 historic air photo in Appendix E. Landslides from the upper areas of the slope continue to occur with the most recent failure in 2008 (Opus Report Reference) visible as the large landslide scar in the western side of the slope in Figure 5.17 A. This large landslide appears to have failed along a planar bedrock surface developed into a debris slide/debris flow towards the bottom of the slope where most of the material crossed the road and entered the river. Due to the distortion of the air photo on the eastern steep bedrock slope it is not possible to view recent rockfall events in the air photo, however, the regrowth of vegetation on the upper slopes suggests it may be in a more stable state than it was when the air photo in 1992 was taken (Appendix E). Generally failure of the regolith materials is not as extensive as it was in 1992. The entire regolith deposit in the centre of the investigation area has been re vegetated with visible debris slides consisting of small displacements of small areas of the slope (Figure 5.17 C), while small displacements of the regolith material high above the highway are unlikely to have a direct impact the presence of one small debris slide on the western side of the large regolith deposit as well as a debris slide below the highway could have a direct impact on highway operation. The largest visible regolith failure is the area east of the highway bridge on the true right bank of the river where a large area of the slope is suffering from debris sliding as a result of river incision an erosion at the toe of the deposit (Figure 5.17 D).

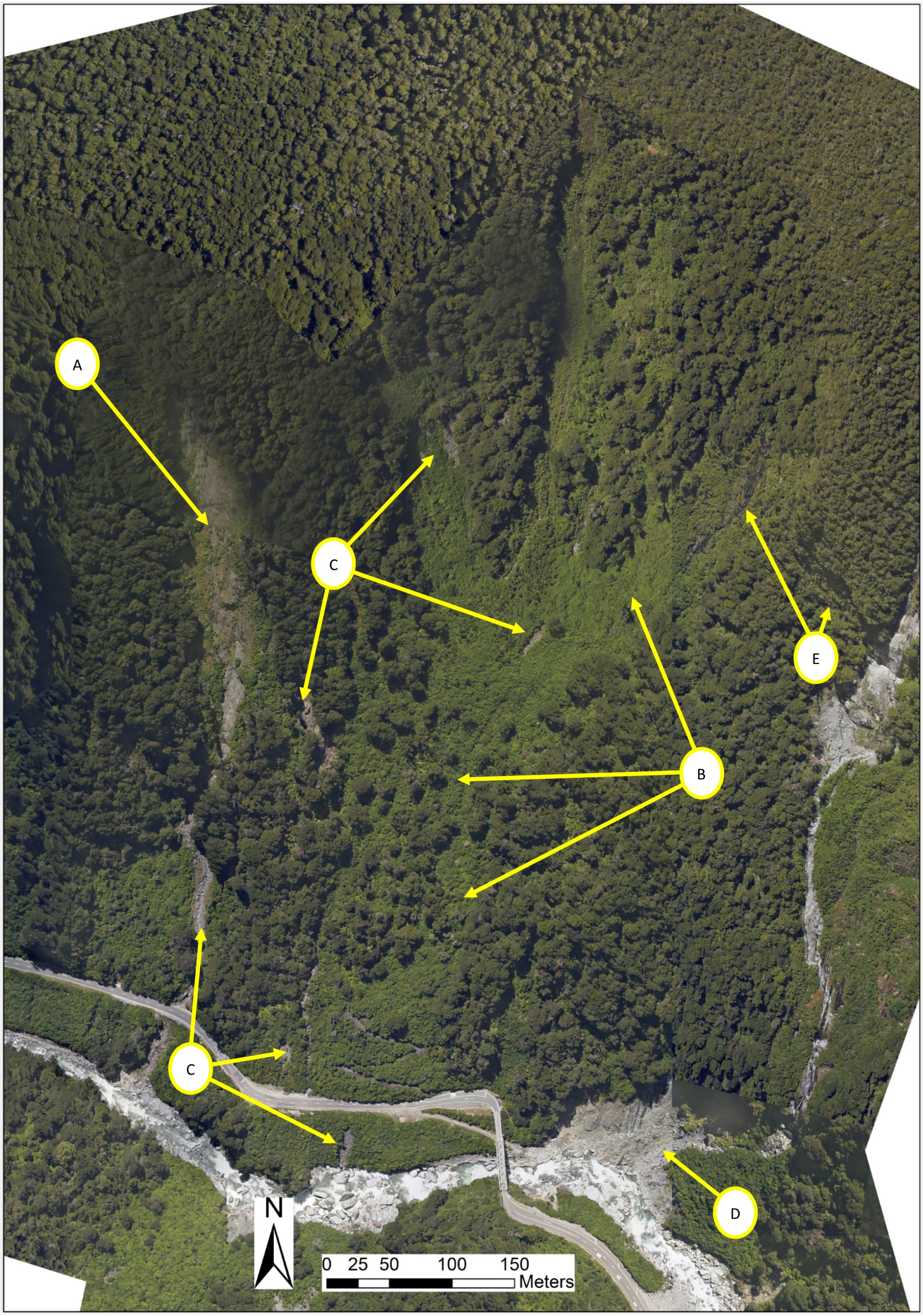

Figure 5.17: Aerial photo of the Gates of Haast investigation area taken in 2014.

5.5.7 Potential for Future Slope Development

It is possible to make broad inferences as to the future development of the slopes above the highway in this area based on the observations in the LiDAR surface, aerial photography and information from previous investigations. While many of the inferences are speculative they are ultimately derived from an understanding of the slope today from various sources as well as an overall appreciation of the large scale geomorphic context of the valley. The steepness of the bedrock on the upper slopes as well as recent rockslides from these areas suggest that the slopes are not in a stable state and further landslides from these areas is to be expected. While the regolith materials above the highway appear to be in a semi-stable state today, long term river incision will continue to erode the toe of the deposits and result in further debris slides. The stabilisation works undertaken by the NZTA in the early 2000's at the Gates of Haast have increased the stability of the slope, however, recent debris slides below the highway visible in the air photo suggest that scour and drop-out of the road will be a problem in the future.

5.6 Synthesis

The detailed evaluation of Diana Falls, Ford Creek, The Hinge and the Gates of Haast and LiDAR was successful at identifying the distribution of surface units, landslide features and slope processes/failure modes as well as extrapolating the subsurface geometry. The current stability was able to be assessed at Diana Falls, the Hinge and the Gates of Haast with all three sites characterised by slopes in a marginal state of stability that will almost certainly continue to present a landslide hazard in the future. The only site where it was not possible to ascertain the current stability or likely future slope development was at Ford Creek where no direct evidence of slope movements was visible in aerial photography. The site specific findings of this chapter are used to inform hazard event avoidance and mitigation options for the entire pass that are discussed in more detail in Chapter 6.

Chapter 6

Slope Hazard Impact and Management

6.1 Introduction

The major slope hazards posing a threat to State Highway Six through the Haast Pass were identified in Chapters three, four and five, and consist of debris flows, debris slides, rock fall and highway collapse. The first sections of this chapter discusses the impact that each of these hazards would have on the highway from a loss of life and highway security perspective. Options to manage the impact of specific hazards as well as the wider corridor are also discussed, outlining the immediate response to an event as well as short and long-term options that can be undertaken to avoid or mitigate the hazard reducing the potential for loss of life or the highway. The final section of this chapter suggests a new management strategy be adopted that focuses on minimising highway closures and reducing the potential for loss of life.

6.2 Debris Flow Impact

6.2.1 Debris Flows in the Haast Pass

Debris flows are mass movements intermediary between landslides and water floods with up to 65% of the mass made up of solid material. Debris flows are often highly channelised and move down slope rapidly at speeds upwards of three metres per second with large boulders able to be carried due to the high density and strength of the viscous mass (Hungr et al. 2013). A number of factors are required to be present at a site for debris flows to be considered a hazard. There must be an available supply of unconsolidated debris and a water source with which to mobilise it. The slope angle of the slope also plays a critical role with most debris slides not occurring on slopes greater than five degrees. The triggering of a debris flow can occur in a number of ways either by water flow entraining material in the debris surface or by a landslide resulting a rapid influx of sediment into a stream that during periods of high flow can result in the sediment being entrained and initiating a debris flow. Once a debris flow is initiated it can travel down slope entraining more material as it moves down slope until it reaches a shallower surface and deposits the suspended sediment. Sites at Wilson Creek in the southern zone and Pipson Creek and the slopes north of the Gates of Haast Bridge in the northern zone have been identified as being exposed to debris flow hazards (See sections 3.4.5, 4.3.5 and 4.4.5). Understanding the factors required for debris flow formation and the behaviour of debris flows as they travel down slope is important as it has a big effect on the expected impact on the highway and the methods that can be used for avoidance and mitigation.

6.2.2 Impact of Debris Flows on the Highway

The highly channelised nature of debris flows means that in most cases tens of metres of the highway is exposed to the hazard, however the impact on that section would be significant. The initial debris flow from the sites are expected to contain hundreds to thousands of cubic metres of debris moving down slope as a fast dense surge of sediment that would quickly inundate the highway and cover it beneath several metres of boulders, cobbles, gravel and vegetation. If there was a vehicle in the hazard zone at the time there is the potential for serious injury, or even death if the vehicle is forced off the road by the surge. Deposition of material onto the highway would also force the roads closure as the highway would be impassable and the debris would need to be cleared. With debris flows commonly occurring during periods of heavy rain, the potential for further debris flows after the initial event means that clearance work would be hazardous during bad weather and could extend the time that the road is closed. Damage to the highway and drainage structures where present would also occur and in most cases seal repairs and culvert repairs would necessary.

6.2.3 Example of Debris Flow Event and Impact

The debris flow that occurred on the 10th September 2013 at Pipson Creek provides the most recent illustration of the impact that these events can have on the highway. During a night of heavy rainfall that triggered numerous other landslides in the Haast Pass a debris flow travelled down Pipson Creek and due to the lack of capacity at the small culvert at road level crossed the highway. Analysis of the air photo of Pipson Creek shows the debris flow path beginning near an area of instability at the apex of the debris fan and travelling all the way to the highway and into the Haast River (Figure 4.2). A 30 metre section of the highway was covered beneath several metres of debris consisting of boulders, cobbles, gravel and trees. This single event was significant enough to close the highway by itself, however, the presence of several other landslides including the very large landslide at Diana Falls contributed to the road being closed for much longer.

The debris flow during the 2013 event resulted in the highway being closed as debris needed to be cleared, a section of the road was damaged and needed to be repaired and the culvert that normally carries Pipson Creek needed to be reconstructed, however, impacts of this event extend beyond disruption and damage to the highway. It was not until several days later that it became apparent that two tourists were missing and had last been seen on the Wanaka side of a landslide at Ford Creek. After several days of searching, wreckage of their campervan was found wrapped around a boulder in the Haast River. The subsequent coroners inquest determined that the tourists had most likely been swept into the Haast River by the debris flow at Pipson Creek, killing them instantly. This highlights that these events not only have the potential to cause significant disruption and damage to the highway itself, but also have the possibility to cause fatalities for the occupants of any vehicle caught in the path, be it a car, campervan or bus.

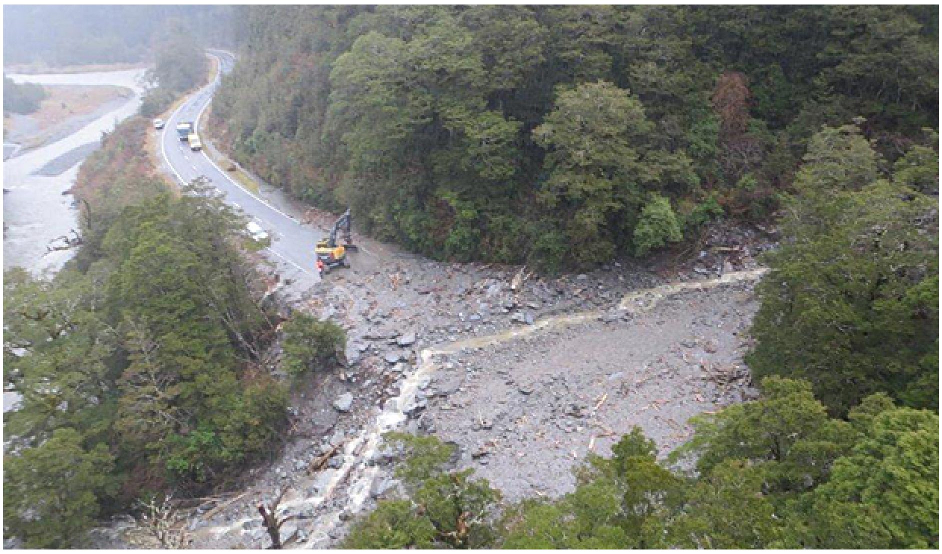

Figure 6.1: This photo shows where the Pipson Creek debris flow crossed the highway covering it in several metres of boulders, cobbles and gravel. It is at this site at two tourists were reported to have been impacted by the debris flow and washed into the Haast River. An excavator can be seen removing material to try and clear the highway (Photo Credit:NZTA).

6.2.4 Potential for Reduction of Debris Flow Impacts

Each of the debris flow hazard sites in the Haast Pass have distinct characteristics that make a one size fits all approach unhelpful. At all of the sites the presence of large quantities of regolith, concentrated stream flow in channels, and unstable surrounding slopes make it almost certain that debris flows will occur again. In the case of Pipson Creek and Wilson Creek the highly channelised nature of the debris flow pathway above the highway means that the same section of highway will be impacted repeatedly. As the same section of the highway is impacted repeatedly, a more proactive approach to managing the hazard needs to be implemented. A similar situation exists at the Gates of Haast, although at this site debris flows are not necessarily constrained to highly channelised pathways increasing the debris flow hazard zone so it covers 100s rather than 10s of metres. Measures to manage debris flow hazards are discussed further in Section 6.6.1.

6.3 Debris Slide Impact

6.3.1 Debris Slides in the Haast Pass

Debris slides are mass movements of regolith material, typically colluvium veneers or deposits sourced from past landslide events, that fail along a relativity planar failure surface. The failure surface can be a rupture within the colluvium or the interface between colluvium and bedrock on steep slopes where bedrock exists at shallow depths. Three key factors are required for a slope to be considered a debris slide hazard. There must be a supply of unconsolidated debris covering the slope. The slope angle also has to be steep enough to promote failure, typically slopes between 30 and 60 degrees are where most debris slides initiate with less than 10% initiating between 20 and 30 degrees. There also has to be a trigger to initiate the failure and in the Haast Pass this is typically intense rainfall that results in an increase in the pore-water pressure and loss of cohesion of the debris. The loss of material from the toe of the slope by either road cuttings, river or earlier debris slides is also going to lead to a reduction of the overall stability of the slope. Some small areas in the southern zone and large areas of the northern zone were identified as being exposed to debris slide hazards (See sections 3.3.5, 3.4.5, 3.5.5, 4.3.5 and 4.4.5). It is important to understand the behaviour and triggers of debris slides as it provides information on the expected impact and ability to avoid or mitigate the hazard.

6.3.2 Impact of Debris Slides on the Highway

The widespread distribution of debris material on the slopes above the highway in the Haast Pass means large areas are exposed to potential inundation, however individual events typically only involve 10m to 100m of highway. The size of debris slides in the hazardous zones differs from the southern to the northern zone with volumes in the southern zone ranging from 100s to 1000s of cubic metres and volumes in the northern zone ranging from 100s to 10000s of cubic metres. Events would result in inundation of the highway beneath several metres of boulders, cobbles and gravel that would result in closure of the road. The initial event would be potentially fatal for any road user in the impact area as boulders could crush and bury a vehicle or result in it being forced off the highway and into the river. If material remains on the slope after the initial failure subsequent debris slides at the same site will probably occur. Continued instability at the site in the weeks, months and potentially years after will make removal of the debris covering the highway hazardous and presents an ongoing instability problem that will need to be dealt with before the highway is reopened.

6.3.3 Example of Debris Slide Event and Impact

The large debris slide episode that began on the 10th September 2013 at Diana Falls provides a recent illustration of the initial and ongoing impacts that debris slides can have on the highway. An initial slide with a volume estimated at 20,000m^3 occurred on the 10th September affecting a 50m section of the highway and resulting in closure for 10 days as further slides and boulders rolling down slope made clearance dangerous. Another large debris slide on the 27th September 2013 resulted in 10,000m^3 of material sliding down slope from the area above the initial head scarp and again resulted in the highway's closure. In the months after the two large debris slides rainfall events continued to initiate smaller slides that resulted in further road closures and clearing works.

The debris slides resulted in severe disruption to highway operation , with the road only open intermittently during the day and closed at night from September 2013 to November 2014. Damage to the highway was extensive with a new surface having to be installed as well as a half bridge and a new culvert to carry the water running over the waterfall. The loss of material from the slope has also left the head scarp and lateral scarps unsupported presenting an ongoing debris slide hazard to the highway. To temporarily deal with this hazard and reopen the highway, rockfall fences and debris drapes have been installed to catch the larger boulders and funnel future debris slides alongside the cliff at highway level and away from the road. While this may work in the short term, the considerable maintenance cost of the fences and concerns with the potential for larger failures at the site was outlined in section 5.2 suggesting that the fences are a short term solution

Figure 6.2: Photo of the Diana Falls debris slide taken after the second large event that resulted in extension of the slide up slope on the 27th September 2013 (Photo taken 30/09). The State Highway Six can be seen running across the bottom of the image with the highway below the slide covered by debris. (Photo Credit:NZTA).

and this site will see further landslides in the future.

6.3.4 Potential for Reduction of Debris Slide Impacts

The size of the debris slide hazard zone combined with the difficulty of detecting precursor movements means that stopping the initial events from occurring or avoiding the impact of the initial event on the highway is practically impossible. While some debris slides do show clear evidence of precursory movements and could be investigated and perhaps prevented, such as Diana Falls where instability was visible in historic air photos, the majority of debris slides do not. This means that a corridor scale management strategy is required to best mitigate the impacts of the initial events. If material remains on the slope after the initial debris slide then the opportunity to reduce and avoid subsequent debris slide events becomes a realistic and feasible option and should be undertaken given the increased likelihood of further failures. Recommendations to effectively manage the debris slide hazard are discussed further in Section 6.6.2.

6.4 Rock fall Impact

6.4.1 Rock fall in the Haast Pass

The definition of rockfall used in the Haast Pass follows Hungr et al. (2013) and is the processes of detachment, falling, rolling and/or bouncing of rock fragments down a slope as single rocks or clusters, with little interaction between the mobile fragments. In the Haast Pass the rockfall hazard zones are associated with potential source areas that include in-situ sources such as steep bedrock slopes and cliffs or steep debris covered slopes containing blocks of schist that could fall onto the highway. The areas that could potentially be impacted by rockfall events are outlined in the hazard identification sections of Chapters three and four (See Sections 3.3.5, 3.5.5, 4.3.5 and 4.4.5). Identifying areas that are potentially susceptible to rockfall events and understanding the impact that they can have on the highway is important as it highlights the problem severity and informs the appropriate measures that can be taken to avoid or mitigate the hazard.

6.4.2 Impact of Rockfall on the Highway

Large sections of the highway in the Haast Pass are potentially exposed to rockfall hazards, but individual failures would only affect 10s of metres of the highway. Individual rocks falling are likely to be on the order of 1m to 5m across with total volumes of rockfall likely to be in the 10s of cubic metres for the cliffs next to the highway, but could be on the order of 100s of cubic metres for some of the larger cliffs in the trees above the highway. The smaller events may not block the highway if only several fragments fall, but larger rocks or a rockfall cluster are likely to inundate the highway and has the potential to directly impact road users who may be struck by a rockfall leading to serious injury of death. The road would likely be closed until the area from which the rock fall originated was inspected and if still unstable would need to be made safe before clearance works could be undertaken. Damage to the highway would vary depending on the energy of the individual impacts that varies on the mass and velocity of the rock as well as the volume of material and in the worst case would likely damage the road surface and structures surrounding.

6.4.3 Example of Rockfall Event and Impact on Highway

Past rockfall events in the Haast Pass have occurred as isolated rockfall events and as a component of debris sliding episodes such as the ongoing problems with individual boulders falling down from the scarp of the Diana Falls landslide. The example provided here is from a well documented rockfall hazard site at the northern approach to the Gates of Haast bridge that was the subject of an engineering report by Paterson (1994). On the 29th September 1994 a rockfall originating from a gully on the northern side of the Gates of Haast bridge resulted in rock debris inundating the highway. The rock debris consisted of boulders between 0.5 and 1 metre in diameter as well as a finer component of cobble sized particles. The investigation noted that the gully that the rockfall was sourced from extended 100 metres above the highway and consisted of boulders between 2 and 4 metres in diameter. The report also noted that the young age of vegetation at the head of the gully suggested that the site had probably been the site of previous rockfall events. The impact of the rockfall on the highway was relatively minor with no damage to the bridge and only superficial damage to the highway as it was unsealed at the time. Luckily no road users were impacted by falling rocks as an impact would probably result in serious injury or death by the impact itself or by being forced off the highway and down the steep bank into the river. The site presented an ongoing hazard as large boulders remained at the head of the gully that could potentially fall onto the highway. The solution reached at this site was to construct a gabion bund at the base of the gully in the approximate location of th debris in Figure 6.3.

Figure 6.3: Photo showing the rock fall gully on the north side of the Gates of Haast bridge. Schist boulders originate from the top of the gully and the unstable right side of the gully. Recent rockfall material can be seen at the base of the gully and consists of boulders between 0.5 and 1 metre across with a finer fraction consisting of cobbles and gravel. The debris has been left in place as a temporary bund to trap subsequent rock fall events (Photo Credit:Engineering Report (Paterson 1994)

6.4.4 Potential for Reduction of Rock fall Impacts

With the majority of the rockfall hazard zones having source areas adjacent to the highway that are accessible, the potential to undertake hazard prevention and mitigation is a realistic option. A proactive approach undertaking stability assessments of the cliffs next to the highway will provide a better understanding of which cliffs are at risk of failure and enables prevention or mitigation work to stop the initial failure for occurring. Assessment of the cliffs higher up the slope is feasible, but would be more time consuming and costly to undertake any prevention or mitigation works. Avoiding or mitigating rockfall originating from regolith slopes is more difficult as the location of the hazard is not as well defined as in the case of the cliffs. Instead rockfall assessment and mitigation in these areas should be undertaken after the initial failure when the location is better understood and in depth investigations can be undertaken. Diana Falls is a good example of a rockfall source originating from regolith covered slopes that has been studied, identified a rockfall risk and then mitigated. Measures to manage the rockfall hazard are discussed further in Section 6.6.3.

6.5 Impact of Highway Collapse

6.5.1 Highway Collapse in the Haast Pass

Collapse of the highway is defined as the displacement of partial loss of the highway surface or margins as a result of mass movements of material beneath the road surface. The mechanism that facilitates highway collapse in the Haast Pass consists of debris sliding of regolith covered slopes below, beneath and sometimes above the highway. The location of highway collapse hazard areas are controlled by two key factors. The first is that the highway must be founded across a regolith deposit or at the top of a regolith veneered slope and the second is that a destabilising influence must be acting on the slope; which in the case of the Haast Pass is down cutting and undercutting effect of the Haast River. This means that in the Haast Pass the highway collapse hazard zones are only found in the northern zone with highway collapse in the southern zone attributed to river erosion directly rather than slope process hazards. Identifying the areas that are susceptible to highway collapse is important as the impacts on the highway range from minor to potentially catastrophic.

6.5.2 Impact of Highway Collapse

The impact of highway collapse varies from minor to catastrophic depending on the characteristics of each site and the extent of the slope failure. Where the highway is only partly built on regolith with a thin veneer extending down slope the debris slide failure would probably only be shallow and result in partial loss of the highway and margin. In many locations where highway collapse is a hazard the scope to move the highway further into the slope is limited due the steep slopes and reinstatement of the collapsed section would require significant earthworks and down slope stability works. Even minor failures such as partial loss of the highway could result in serious injury or death if a road user did not see that part of the highway had collapsed. In areas where the highway is built entirely across regolith deposits the same impacts as above apply, however, the potential exists for much more substantial deep seated debris slide failures to result severe impacts on the highway.

Small creeping debris slide movements would result in deformation of the highway surface that would require ongoing maintenance to keep it serviceable, but are unlikely to result in closure of the highway. These slowly creeping debris slides need to be well understood and managed as they can develop into more rapid debris slide movements that could result in total slope failure. If total slope failure was to occur, sections of the highway would be lost resulting in lengthy road closures. The area surrounding the slide area would probably also be in a marginal state of stability and remediation of theses areas would need to be undertaken and significant earthworks would be required to reinstate the highway. The potential for serious injury or death of road users is greater than other slope hazards as larger sections of the highway can be affected with failure involving up to 100m of highway.

6.5.3 Example of Highway Collapse and Impact on Highway

Sections of the highway in the Haast Pass have been lost to highway collapse in the past with a number of locations posing ongoing stability problems. The area known as The Hinge provides a well documented example of a partial highway collapse as a result of debris sliding that has been well studied by past engineering reports (Opus 2001) and was the focus of detailed LiDAR evaluation in Chapter 5 (See Section 5.4). On the 27th December 2000, a 120m section of highway south of The Hinge slumped 650mm following a period of heavy rainfall. While the section of the highway was being repaired it slumped again on two more occasions and was continuing to slump at a rate of 2.5mm per week two months after the initial failure.

Damage to the highway consisted of a number of holes that had opened in the road surface that were allowing water into the slope and damage at both ends of the slope where half metre scarps had broken the road surface (Figure 6.4). The highway suffered some disruption, but as Figure 6.4 shows vehicles were still able to travel across the affected section. Remediation work consisted of infilling the collapsed section of the road with 500mm of engineered fill and then resealing of the highway. A month after the resealing had taken place there was evidence of continued creep of the debris slide as cracks began to appear in the new seal and water was entering through new swallow holes on the up slope side allowing water to travel beneath the highway.

Slumping of the highway has been an ongoing problem at the site with the seal having to be repaired periodically as movement continues and as such is monitored closely (E. Stevens, personal communication, April 21, 2014). The debris slides appears to have been mobilised by heavy rainfall combined with erosion of the toe of the slope by the Haast River 100 metres below the road at the site of the photo in Figure 6.4. Highway collapse will continue to be a problem at this site and at many other sites as heavy rainfall and undercutting of slopes in the northern zone continues to drive debris sliding.

6.5.4 Potential for Reduction of Highway Collapse Impacts

Reducing the impacts of highway collapses in the Haast Pass is difficult as large sections of the highway are exposed to the hazard and the slopes in question typically are steep and inaccessible. The steep slopes combined with the erosive nature of the Haast River in the hazard areas means that future collapses will occur and engineering solutions to avoid collapse are probably unrealistic, costly and of limited long-term effectiveness. A proactive approach to monitoring the hazard areas, particularly the slopes below the highway, is the most appropriate option with short and long-term solutions implemented on a case by case basis. Measures to manage the hazard and minimise the impact of a highway collapse event are discussed further in Section 6.6.4.

Figure 6.4: Photo of the highway at The Hinge showing the effects of a partial collapse of the highway. A 120 metre section of the highway dropped 650mm and the effect of this drop-out can be seen in the image. The photographer is standing on the dropped section of highway with a scarp visible just in front of the white car and the sinkhole on the left side of the highway in the bottom right corner (Photo Credit:Engineering Report (Opus 2001))

6.6 Hazard Specific Management Strategies

6.6.1 Debris Flow Hazard Management

With the highway alignment fixed in place and with little scope to move the highway to avoid future debris flows, management must focus on reducing the impact of debris flow events on the current alignment to ensure route security and life safety. The current debris flow hazard management approach in the Haast Pass is restricted to responding to events after their occurrence with the management of the immediate response outlined in Table 6.1. This approach does not minimise the impacts of debris flow events on route security or take available steps to ensure life safety in areas where it is technically feasible. Instead of reacting to debris flow events there are short and long-term measures that can be implemented.

Short-term solutions, outlined in Table 6.1, are aimed at reducing the impact of debris flow events on the highway within the debris flow hazard zones. They are considered to be short-term solutions as they require extensive maintenance, replacement and do not avoid the hazard, but do significantly reduce the impact and potential for loss of life. The long term management options, outlined in Table 6.1, provide options to avoid debris flows hazards allowing the events to take place and not impact the highway; the long-term options are the only options that guarantee route security and safeguard against loss of life within the debris flow hazard zones. The areas around Pipson Creek and Wilson Creek in particular provide opportunities to completely avoid debris flow hazards while the area around the Gates of Haast is more challenging due to the large hazard area and options for limited long term hazard management.

Table 6.1: Debris Flow Hazard Management Options

Debris Flow Hazard Management Options				
Location	Hazard Impact	Immediate Response to Event	Short-Term Solutions (0-10 Years)	Long-Term Solutions (10+ Years)
Wilson Creek and Pipson Creek	• Small hazard zone tens of metres wide. • Inundation of Highway. • Road closed for several days. • Damage to Highway surface and associated structures. • Potential for loss of life.	• Manned Road Closures. • Geotechnical inspection and assessment of source area, runout zone and deposit. • Earthworks to remove material from highway. • Stabilization works if geotechnical assessment finds material upslope is unstable.	• Warning signage to advise motorists of hazard area and no stopping. • Debris flow attenuators in creek bed. Accumulated debris will need to be removed after debris flow events. • Stabilization of source area. • Investigation of alternative alignments.	• Bridging over the creeks providing accommodation space for debris flows to pass beneath. This option will require ongoing maintenance to clear debris and keep the highway safe from future events. • Warning system that triggers when debris gets close to the bridge level and automatically closes the road/ bridge.
Gates of Haast	• Hazard area up to 100 metres wide • Inundation of Highway. • Road closed for several days. • Damage to Highway surface and associated structures. • Potential for loss of life.		• Warning signage to advise motorists of hazard area and no stopping.	• Avoiding the hazard area by bridging to other side of valley. Based on the findings of the alternative alignment investigation.

6.6.2 Debris Slide Hazard Management

The nature of debris slides in the Haast Pass makes identifying precursor movements difficult and unreliable; in this case a reactive management approach to initial debris slides is most appropriate with proactive hazard management approach implemented to manage the future debris slides from the site. The difficulties with mitigating or avoiding the initial debris slide hazard means that an effective management strategy centres on a corridor wide management strategy rather than on treatment of a particularity hazardous area and is covered in more detail in Section 6.7. The initial response to a debris slide event is focused on assessment and ensuring safety of personnel removing debris from the highway with the aim of attaining a partial opening of the highway with active monitoring of the unstable areas (outlined in Table 6.2). Short-term options to manage the on going hazard posed by unstable material within and around the initial debris slide are focused on providing temporary route security; detailed geotechnical investigations must follow the initial event to understand the potential for further debris slides and evaluate if short-term solutions will last or if continued debris slide events will inundating and overwhelm the short-term options.

If detailed geotechnical investigations find that continued instability will be an ongoing problem in the future then more long-term options are required to ensure route security and guarantee life safety through the hazard zone. The initial cost of long-term options, outlined in Table 6.2, would be more costly than the temporary short-term options, but provide long-term route security, life safety benefits and over the life of the highway a more sustainable alternative. Major capital works involving bridging and substantial highway realignment are an option for avoiding the hazards, but evaluation of this option is outside the scope of this thesis and would require detailed LiDAR evaluation of the slopes on the other side of the valley.

Table 6.2: Debris Slide Hazard Management Options

Debris Slide Hazard Management Options				
Location	Hazard Impact	Immediate Response	Short-Term Solutions (0-10 Years)	Long-Term Solutions (10+ Years)
Southern and Northern Zones (Post Debris slide Event)	• Large areas of highway in Northern zone and some areas in Southern Zone. • Inundation of Highway. • Ongoing instability issues • Road closed for several days. • Damage to Highway surface and associated structures. • Potential for loss of life.	• Initial geotechnical inspection and assessment of source area, runout zone and deposit. • Active slope monitoring for instability. • Earthworks to remove material from highway. • Manned road closures at night when debris movements not visible. • Stabilization works if geotechnical assessment finds material upslope is unstable.	• Detailed geotechnical investigation of slide area and surroundings to understand the geometry and failure processes. Using LiDAR to provide big picture context. • Warning signage to advise motorists that they are in a hazardous area and should not stop. • Sluicing of debris off slope (If debris is not deep). • Installation of Rockfall and debris slide catch fences.	• Rockfall/debris shelter over road. • Road realignment away from debris slide hazard areas.

6.6.3 Rockfall Hazard Management

With most rockfall hazard sources being located next or close to the highway it is feasible to undertake proactive management to avoid or minimise the impact of an event originating from these areas. Where rockfall events originate far above the highway the options to avoid or mitigate the hazard are limited, with areas such as the steep bedrock slopes above the Gates of Haast providing a large and inaccessible source area. During ground truthing exercises, brief visual inspections and limited joint measurements were undertaken on rock masses next to the highway, finding most cliffs appeared unstable, but lacked adequate joints to form release blocks (see Section 4.3.5); the brief inspection is inadequate to evaluate the stability of the cliffs and mitigation of this potential hazard begins with a more through geotechnical evaluation of the rock masses both next to and close to the highway. From this work the rock masses that are unstable can be identified and appropriate mitigation measures can be implemented, see Table 6.3. Beyond major capital works to realign the highway, the options to avoid or mitigate the hazard posed by rockfall from the cliffs above the Gates of Haast is limited; to reduce the possibility of a rockfall event from this area resulting in serious injury or death of road users, a corridor scale management approach is required and is discussed further in Section 6.7.

Table 6.3: Rock Fall Hazard Management Options

<table>
<tr><th colspan="4">Rockfall Hazard Management Options</th></tr>
<tr><th>Location</th><th>Hazard Impact</th><th>Immediate Implementation</th><th>Engineered Solutions</th></tr>
<tr><td>Cliffs Next to Highway</td><td>• Inundation of Highway.
• Road closed for hours to days.
• Damage to Highway surface and associated structures.
• Potential for loss of life.</td><td rowspan="2">• Geotechnical inspection of cliffs next to the highway collecting rockmass data for initial assessment and selective modeling of unstable cliffs.
• Instillation of bunds where space is available.
• Removal of unstable rocks.</td><td>• Cliff stability assessments.
• Identification of hazardous areas.
• Warning signage around hazardous areas.
• Rock bolting.
• Mesh drapes.</td></tr>
<tr><td>Cliffs between Robinson and Pipson Creeks</td><td>• Inundation of Highway possible.
• Road closed for hours to days.
• Damage to Highway surface and associated structures.
• Potential for loss of life.</td><td>• Warning signage around hazardous areas.
• Rock bolting.
• Rock fall fences below source areas or adjacent to highway.</td></tr>
</table>

6.6.4 Highway Collapse Hazard Management

There are effective management options to deal with the impacts highway collapse where the highway is partially built on regolith with feasible short and long-term options available to mitigate and avoid the hazard. The options to mitigate or avoid highway collapse hazards where the highway is entirely built across regolith deposits are limited along the present highway alignment. The short-term management options aim to secure route security and reduce the potential for highway disruption, but do not prevent a similar event happening at the same location (options outlined in Table 6.4. Long-term options do exist for sections of road only partially built on regolith cover with feasible engineering solutions outlined in Table 6.4), however, long-term options for sections of the highway entirely build across regolith deposits are limited. Beyond ongoing monitoring of areas suffering from highway collapse the only to achieve route security and guarantee live safety is to undertake major capital works to realign the highway in these areas. It may be the case that no alternative alignments can provide guaranteed long-term route security for some sections of the highway and in these cases management of these hazards shifts to a life safety focus, with an emphasis on a corridor wide management strategy aimed at avoiding loss of life the most appropriate management option in these circumstances (See Section 6.7).

Table 6.4: Highway collapse Hazard Management Options

Highway Collapse Hazard Management				
Location	Hazard Impact	Immediate Response to Event	Short-Term Solutions (0-10 Years)	Long-Term Solutions (10+ Years)
Partly Built on Regolith	• Partial loss of highway. • Road disruption for days to weeks. • Potential for loss of life.	• Road Closure. • Initial geotechnical assessment. • Temporary down slope stabilization and earthworks to reinstate and stabilize the highway.	• Increased signage warning motorists that area is susceptible to highway collapse and to be aware for collapsed sections of highway. • Dumping of material over the side of the highway to replace the lost material. • Instillation of retaining structure down slope to stop loss of debris. May be difficult to find an acceptable foundation for such a structure.	• Ongoing monitoring of areas below the highway to anticipate failures. • Realignment of highway further into hillside onto bedrock. • Construction of half bridges to build across the regolith material with the remainder of the road founded on bedrock.
Entirely Built Across Regolith	• Partial to catastrophic loss of highway. • Potential for loss of life.	• Road closure. • Detailed geotechnical assessment.	• Increased signage warning motorists that area is susceptible to highway collapse and to be aware for collapsed sections of highway. • Active monitoring of affected areas with inclinometers, piezometers and surveys of the road surface to monitor movements. • Dewatering of slope if debris sliding is the collapse mechanism.	• Detailed long-term monitoring of large highway collapse areas. • Highway realignment away from affected areas.

6.7 Corridor Scale Hazard Management Options

6.7.1 Relocation of Pass Closure Gates

The large scale engineering geomorphology and hazard identification undertaken for the slopes above the highway has revealed that the current location of the highway closure gates leave hazardous sections of the highway open to road users. While the road is normally closed at Haast Township and Makarora, the presence of two DoC camp grounds within the closed section of highway means that the only way to keep all potential road users out of the pass is to close the road at these gates. The northern gate is located 50 metres east of Thunder Creek falls car park and the southern gate is located 100 metres north of Pipson Creek. The northern gate is within a potential debris slide zone meaning anybody in the vicinity of the gate would potentially be impacted debris slide and as a result its current location is considered a potential life safety risk. The same issue is present at the southern gate, however, the southern gate leaves larger sections of the highway open to multiple potential hazards; hazards include debris sliding of the Pipson Creek debris fans and regolith deposits between Robinson Creek and Pipson Creek, rockfall from the cliffs above the highway between Robinson and Pipson Creeks, and debris flows from Pipson Creek itself presenting a considerable life safety risk.

The northern gate should be moved further north out of the hazardous area with the Pleasant Flat highway bridge, 3.5km north, providing a suitable slope hazard free zone with which road users would be safe. The southern gate should be moved south to at least beyond Cross Creek near the summit of the Haast Pass to keep road users out of the debris slide, debris flow and rockfall hazard zones. Moving the Pass closure gates would reduce the potential for a fatality for road users either ignoring the road closures signs at Makarora or Haast, or road users leaving from one of the camp sites within the larger highway closure area. Given the ease with which this measure could be implemented it should be completed as soon as possible.

6.7.2 Repeated Systematic Aerial Photo Reconnaissance Surveys

Repeated systematic aerial reconnaissance surveys should be undertaken annually or bi-annually in order for changes in the slopes above the highway to be identified and compared through time. The photos would serve as an ongoing corridor scale monitoring strategy that could potentially identify precursor movements to landslide events, enabling monitoring and investigation to be undertaken to assess the potential for failure. The survey could be undertaken using an aerial photography camera capable of generating stereoscopic pairs on either a helicopter of fixed wing aircraft enabling the survey to be completed quickly and safely. The key to this approach is that the gathering of aerial photos must be systematic, repeated annually or bi-annually and analysis work must be undertaken by personnel trained in aerial photo interpretation, and with a knowledge of the failures that they are looking for. Overall this method provides a cost effective way of monitoring the slopes above the highway on an ongoing basis.

6.7.3 Development of a Landslide Event Database

Development of a landslide event database should be undertaken with the aim of keeping a systematic record of all mass movement occurrences in the Haast Pass. This database would be used to track the event type, size, location and antecedent weather conditions when the event is discovered that would over time provide information on the patterns of active instability and potentially provide information on areas that may be close to total failure. Information would be entered into the database by roading contractors clearing material off the highway and by highway engineers during routine checks. The widespread use of smartphones and newly added cell phone coverage in the Haast Pass means that a smart phone application that could be filled in by contractors may be the best way of entering data into the database. Ultimately this database is essential for developing of an empirical relationship between landslide occurrence and precipitation intensity/duration and is discussed in the Section 6.7.4 below.

6.7.4 Development of Landslide Rainfall Relationships

With landslide activity in the Haast Pass largely triggered by rainfall the potential exists to minimise the life safety risk through the development of a landslide-rainfall relationship to drive decision making on highway closures due to adverse weather conditions. The landslide-rainfall relationships are site specific and the first step in developing this relationship for the Haast Pass is to begin collecting detailed precipitation information from within the Pass itself. Auto-logging rain gauges should be installed through the pass with one placed near the Gates of Haast Bridge, one near Pipson Creek, and one near the summit of the Haast Pass to account for the variability in precipitation across the main divide. The rainfall data is then combined with the landslide event database to evaluate the rainfall thresholds that landslide events begin to occur. Initially a review of landslide-rainfall relationships in similar environments and geology should be undertaken to get a baseline that can be used while data is built up in landslide event database. Eventually with enough information from the rainfall measurements within the pass and from the landslide database and empirical relationship between rainfall and landslide occurrence could be drawn. This empirical relationship would serve to advise highway managers when landslides are probably going to occur, enabling the highway to be closed and preventing loss of life from the unavoidable hazards or those unable to be mitigated.

6.8 Future Corridor Management Strategy

The current management strategy for addressing slope hazards in the Haast Pass is based on a reactive approach to landslide hazards and does not take available actions to minimise the potential for loss of life or ensure route security. The overall approach to risk management that the NZTA takes is focused strictly on road safety with little regard to landslide hazard risk management until it directly impacts on the highway (NZTA 2004, 2007, 2013). This means that the current management approach fails to establish the overall landslide risk context of the corridor and thus, fails to identify, analyse, evaluate and treat the risks that pose a threat to life safety and highway security. This deficiency in the management of landslide hazards is a wider problem that needs to be addressed at a national level, however, within the Haast Pass a new management approach is proposed to deal with the deficiency and better manage the landslide hazards.

The new management approach for the Haast Pass is broken down into steps that can be implemented immediately, in the short-term and long-term in order to effectively manage the landslide hazards facing the highway. The steps to be taken are summarised in Table 6.5 and are discussed in more detail in the sub headings below.

Table 6.5: Outline of Future Corridor Management.

Future Corridor Management Strategy			
Location	Immediate	Short-Term(0-10 Years)	Long-Term (10+ Years)
Corridor Management Strategies	• Installation of hazardous zone signage. • Movement of highway closure gates. • Installation, recording and storage of data from rainfall gauges within the Pass. • Develop and implement hazard event database. • Perform literature review to develop a conservative landslide-rainfall threshold for road closures. • Undertake systematic aerial photo resonance survey and compare with LiDAR survey aerial photos. • Closely monitor the rock fall fences installed at Diana Falls to evaluate their performance. • Undertaken feasibility studies for permeant solutions to avoid the hazard posed by debris flows and debris slides where feasible.	• Closely monitor the rock fall fences installed at Diana Falls to evaluate their performance. • Undertaken feasibility studies for permeant solutions to avoid the hazard posed by debris flows and debris slides where feasible. • Detailed geotechnical investigations at the Diana Falls debris slide to examine the feasibility of permanent solutions. • Detailed geotechnical inspection of highway cliffs, identifying unstable areas that can be remediated. • Detailed geotechnical inspection of highway collapse areas with inclinometers, piezometers and continued surveys to monitor movement. • Rock bolting, mesh drapes and Rockfall fences for hazardous cliffs. • Instillation of debris flow attenuators. • Stabilization of debris flow source areas. • Dumping material over the side of the highway to protect the highway from minor highway collapses.	• Investigate highway realignment options to avoid the more serious and less manageable slope hazards. • If a feasible and safer alternative alignment is identified then highway realignment away form hazardous areas should be undertaken. • Installation of bridges over debris flow creeks to avoid the hazard. • Rockfall Shelter to provide a permanent solution at Diana Falls avoiding continued future instability. • Bridging structures over Pipson and Wilson Creeks to avoid the debris flow hazards • Road realignment where mitigation or avoidance are not possible.

6.8.1 Immediate Options

There are several steps that can be implemented immediately to increase the safety of road users and begin to gather the information required for the short and long-term options. The current location of the highway closure gates allows road users to access hazardous sections of the Pass when it is closed. Moving the highway closures gates out of the hazardous areas to at least the summit of the Pass and pleasant flat camp ground would keep road users safe and provide an area to wait or turn back safely. Similarly, installation of signage within hazardous zones warning road users of the dangers and advising them not to stop or wait in these areas would reduce the potential for them to be affected and increase their awareness and ability to respond.

At present there is limited data available to enable corridor managers to accurately predict when a landslide might occur along the Haast Pass highway. The installation of rain gauges within the Pass to gather accurate rainfall data and development of a landslide event database are critical to the development an empirical relationship between rainfall and landslide occurrence that will be used to manage highway closures in the short and long-term. Until enough landslide data is available development of rainfall thresholds to triggering landslides should be based on a literature review of similar areas to set initial thresholds for road closure. As more landslide events are recorded the initial literature review thresholds can be replaced with empirical relationships calibrated specifically for the Haast Pass.

The development of and on going programme of repeated aerial photo reconnaissance surveys should be considered immediately with the aim of identifying development of slope hazards as their effects are made visible in the overlying vegetation. Interpretations should be made using aerial photos to provide the indicators of changes in the slope and the LiDAR surface providing the context with which to interpret the photos. Due to the variability in filtering of the vegetation when creating the LiDAR surface detecting these changes would be unlikely.

6.8.2 Short-Term Options

Managing landslide hazards in the Haast Pass in the short-term (0-10 Years) requires a commitment to the proactive approach of continued monitoring, hazard recording and investigation. Detailed geotechnical investigations should be carried out at a number of locations to fully understand the hazards and enable design of appropriate mitigation options. At Diana Falls further investigation is needed of the larger debris slide area to attain accurate subsurface information before more long-term solutions can be implemented. A formal geotechnical assessment of the cliffs next to the highway should be undertaken to identify unstable sections enabling appropriate mitigation options to be implemented. Areas suceptable to highway collapse and especially the areas around The Hinge and the Gates of Haast should be closely monitored to identify if any movements of the slopes either begins to move and accelerates.

To mitigate the effects of slope hazards in the short term, management options are available. At Diana Falls rock fall catch fences and a debris drape curtain have been installed and are appropriate short-term solutions to address the residual hazard posed by debris slides. The rockfall catch fence and drapes do not provide suitable long-term options and require extensive monitoring and maintenance to keep them effective. Mitigating potential rock fall hazards from the cliffs next to the highway can be accomplished with rock bolting, mesh drapes and rockfall catch fences and their close proximity to the highway would make monitoring of their performance straightforward.

Managing partial highway collapse events in the short-term can be accomplished effectively by dumping material down slope where it is being lost. However, this option is not effective for mitigating against large highway collapse events where long-term solutions are the only effective means of mitigation.

Short-term options for addressing the debris flows hazards at Pipson and Wilson Creeks consist of instillation of debris flow attenuators to trap and stop debris from impacting the highway. On going maintenance will be required after each event. This option does not completely mitigate the hazard.

6.8.3 Long-Term Options

Long-term options are available to completely avoid landslide hazards from debris flows and the residual hazard posed by debris slides. Where debris slide hazard zones are small in size due to being highly channelised it is feasible to engineer structure to avoid future debris slides from impacting the highway. At Pipson Creek and Wilson creek the hazard zones are narrow and a bridge structure carrying the road higher above the creeks would create sufficient accommodation space for debris flows to pass beneath. This option would require periodic maintenance to ensure that adequate clearance is kept between the creek bed and the bridge deck. Implementing this option would make the highway safer in these areas and ensure route security long-term.

Options also exist to avoid the impact of rockfall and debris slides from areas that have already experienced large slope failures and continue to shed material. In these cases construction of rock fall/debris slide shelters over the highway to allow material to travel over the highway and carry on down slope without affecting the highway. Diana Falls is a prime example of a location where a shelter could be built to carry material falling down slope over the highway. However, it is not feasible to construct rockfall shelters to avoid the initial debris slide events and in these cases large scale road realignments are the recommended option.

In areas where mitigation and avoidance of the hazard affecting the highway are not feasible then long-term route security and hazards avoidance must switch to identifying alternative highway alignments. These areas include the Gates of Haast where the debris slide hazard zone is extensive making an engineered solution impracticable. This option might also be considered to avoid debris slide hazards between Pipson Creek and The Hinge. Similarly at The Hinge and the Gates of Haast where the highway is built on regolith, and highway collapse is likely to be an on going hazard highway realignment should be considered. Further investigations are required before alternative highway alignments can be recommended, however, the results may show that the current highway alignment is the least hazardous option.

Chapter 7

Conclusions

7.1 Thesis Objectives

The objectives of the thesis were set out in Chapter One and are restated below;

1. Evaluate if a combination of LiDAR, aerial photo analysis and targeted ground truthing can be used to reliably identify surface units, landslides and slope processes beneath dense vegetation in the Haast Pass.

2. Undertake large scale engineering geomorphology mapping of surface units, slope processes and landslide features within the Haast Pass primarily using LiDAR. The aim of mapping the hillslope geomorphology was to identify potential slope hazards and prioritise a number of selected hazardous slopes for more detailed engineering geomorphology investigations.

3. Undertake small scale engineering geomorphological investigations at four selected hazardous sites based on the findings of the large-scale LiDAR analysis identifying surface units, landslide features, subsurface geometry, failure mechanisms, current slope stability and future slope development.

4. Use the large-scale and small-scale engineering geomorphology investigations to identify hazards the highway is exposed to and propose methods of avoidance, mitigation and corridor wide management that can be implemented to reduce the impacts that the hazards have on the highway.

7.2 Thesis Methodology

The use of LiDAR to image the ground surface beneath vegetation in the Haast Pass has enabled an unprecedented level of detail to be extracted from the slopes above the highway. This is the first time this technique has been successfully applied to inform highway corridor management. The high resolution ground surface model enabled regolith and bedrock surfaces to be distinguished with slope processes inferred from relationships between landforms. It also enabled landslide structures to be easily identified with scarps and hummocky ground easily distinguishable in the LiDAR surface that were unable to be readily identified on the ground where dense vegetation and ground clutter obscures the larger scale landslide structures. One of the most important steps of using LiDAR for mapping the surface units and slope processes was validation of initial LiDAR analysis. This was achieved by using aerial photos and ground truthing to ensure accuracy of interpretation.

This thesis has demonstrated the effectiveness of using LiDAR to provide the large scale geomorphic context to a highway corridor enabling hazard identification and evaluation to be undertaken.

LiDAR has facilitated the production of high quality surface models in areas of dense vegetation, providing more detailed information than more traditional techniques. Large areas of slope along a highway corridor can be mapped quickly, providing a relatively inexpensive way to attain accurate slope hazard information. LiDAR geomorphology/landslide hazard mapping can and should be applied across the New Zealand state highway network in areas where landslides are likely to be a problem and where slopes are obscured by dense vegetation.

7.3 Corridor-Scale Assessment

A distinct contrast exists between the geomorphology of the southern zone and that of the northern zone. The southern zone is largely composed of schist bedrock with minor deposits of regolith deposited on locally oversteepened slopes next to the highway. With the exception of the regolith deposits north of Robinson Creek, nearly all slopes facing the highway in the southern zone appear to be inactive. The active slopes in the southern zone are only found in the steep tributary valleys feeding into the Haast River.

In contrast the slopes of the northern zone are predominantly covered with regolith both above and below the highway through the entire zone with the thickest deposits of regolith found at the Pipson Creek Fans, The Hinge and slopes west of the Gates of Haast Bridge. Slopes above the highway in the northern zone show active and recently active slope processes with recent debris flows and debris slides clearly visible. Large areas, west of the Gates of Haast bridge, appear to be some of the most active areas in the pass.

Based on the findings of the large scale LiDAR geomorphology, a number of potential slopes hazards have been identified with clear hazard patterns emerging between the southern and northern zones. In the southern zone slope hazards and confined to short sections of highway with the primary hazard consisting of debris sliding. The potential for rockfall from cliffs next the highway also exists between Robinson and Pipson Creeks. The entire northern zone, in contrast to the southern zone, is exposed to either debris sliding, debris flows, rockfall or highway collapse with many sections exposed to a combination of these hazards. This is the first time that the potential slopes hazards facing the highway have been recognised, enabling a better understanding of the location, impact and information for improved management of the landslide hazards in the Haast Pass.

7.4 Detailed Hazard Evaluation

7.4.1 Diana Falls

The detailed small scale LiDAR evaluation of Diana Falls identified surface units, landslide features, failure mechanisms and extrapolation of subsurface geometry. The investigation revealed that a much larger landslide scarp exists above and around the 2013 debris slide failure, with the regolith material within displaying signs of instability. Based on the overall landslide morphology and displaced large rock masses, the most likely failure scenario for the larger landslide area is one of small debris slides from the surface with the potential for deep seated displacement of large bedrock blocks also occurring. It is clear from these signs that future instability originating from the slopes within the large landslide headscarp will continue to be an issue into the future at Diana Falls and that management decisions will need to look to long term options to avoid or mitigate the impacts on the highway and its road users.

7.4.2 Ford Creek Landslide

Detailed small-scale geomorphology investigations at Ford Creek identified surface units, landslide features, failure mechanisms and extrapolation of subsurface geometry, but was unable to assess the current stability of the landslide due to dense vegetation cover and the probable slow creeping nature of the slide. The landslide is a deep seated rock compound slide with a failure surface stepping primarily along a shallowly dipping defect to a lesser extent foliation based on the surface expression in the LiDAR surface. The large gully in its southern section shows signs of debris sliding and rockfall from the steep gulley sides. Based on its probable slow creeping nature this landslide should be monitored routinely, but with more in depth investigations focused in other areas of the pass where the landslide hazards are more well understood and pose a more direct and imminent threat.

7.4.3 The Hinge

The landslide at The Hinge has a history of debris sliding that has resulted in highway collapse. The detailed small-scale slope evaluation identified the headscarp and lateral scarps of the large creeping debris slide that is resulting in continued highway collapse. Evidence of mass movements of regolith material, both above the highway in the northern end of the investigation area, and throughout the slopes below the highway. The presence of the scarps below the highway indicates that the lower slope is very unstable and presents a significant highway collapse hazard in this area. The instability is largely being driven by the Haast River incising and eroding the toe of the slope. The Hinge and other sites with regolith materials below the highway, where the Haast River is highly erosive, will continue to pose a highway collapse hazard in the future and appropriate steps need to be taken to avoid or mitigate the impacts of theses events.

7.4.4 The Gates of Haast

At the Gates of Haast investigations have provided a wider context to the rocksliding and debris sliding problems experienced at the site in the past. The investigation established that the lower slope is predominately composed of regolith up to 50m thick with narrow bedrock ridges extending to the bedrock dominated upper slopes. Result show the highway is built across deep regolith deposits making it susceptible to river erosion leading to highway collapse. Hazards above the highway include rocksliding,debris flows and deep seated debris sliding from the main regolith deposits. The large areas covered with young/immature vegetation on the slopes in this area confirm that many of these hazards have been active and indicate that the overall slope is in a marginal state of stability.

7.5 Proposed Hazard Management Strategy

The slope hazards identified during the large and small scale geomorphology investigations highlighted debris flows, debris slides, rockfall and highway collapse as the main hazards to the highway and road users. All of these hazards have the potential to close the highway for a significant length of time, cause significant damage to the highway and pose a very real threat to road users. Feasible solutions are available to avoid or mitigate the impacts of debris flows, rockfall events and post debris slide instability by undertaking detailed assessments and design of suitable engineered solutions.

This thesis provides suggestions for better highway corridor management that the strategies that currently exist. The Haast Pass highway is situated in a remote area, so it is important to avoid or mitigate as many hazards as is feasible to keep the highway open. Options for immediate and longer-term solutions have been highlighted and include low cost solutions as simple as providing warning sighs to larger capital works such as road realignment.

The current management strategy for dealing with slope instability in the Haast Pass is based on a reactive approach to landslide events and fails to take all available steps to adequately address hazard. A new management, as suggested in this study does not follow the conventional investigation methodology used by NZTA and others in the past. Using LiDAR, in collaboration with ground truthing and aerial photos, this thesis has demonstrated that it is now possible to clearly identify specific areas along the highway corridor that have the potential to close the highway. Specific sites particularly in the northern section of the field areas between Pipson Creek and the Gates of Haast have been outlined in detail throughout this study.

A corridor wide management strategy should involve more proactive monitoring of the slopes above the highway, than occurs at present. This study recommends repeated systematic aerial reconnaissance surveys be undertaken to identify new areas of instability and build a wider picture of the changes occurring in the slope through time. Ultimately the development of a landslide rainfall relationship based on a hazardous slope event database for the pass, combined with accurate precipitation data from within the pass itself, will serve to advise highway managers of the weather conditions likely to trigger landslide events enabling the road to be closed and preventing loss of life.

7.6 Future Research

Outlined below are recommendations for further investigations in the Haast Pass to get a better understanding of the more hazardous sites and to better understand the frequency with which events originate from these areas. Recommendations for the application of the methodology outlined in this study area also covered.

1. Further investigation works should be undertaken at Diana Falls to better constrain the subsurface geometry and identify the failure surface of the larger global failure. Works should include drilling through the main body of the landslide from within the large landslide scarp with more detailed ground mapping to confirm the scarps identified in LiDAR and identify

those that were not detectable.

2. Further investigations at Pipson Creek should be undertaken to better constrain the frequency of debris flow events on the fan. This could be completed using dendrochronology to identify the vegetation age across the fan and on the margins of the creek. Since the debris flow that impacted the highway on the 10th September 2013 appears to have initiated at the apex of the northern fan, further geotechnical investigations into the overall stability of this area should be undertaken.

3. Further geotechnical investigations of the regolith deposits above the Wilson Creek gorge should be completed as a large landslide from the deposit has the potential to block the river. Blocking and subsequent breaching of a landslide dam could result in a rapid release of water and debris down the gorge that could impact the highway. Minor landslides may initiate debris flows, especially where the river enters the gorge and water flow becomes more concentrated.

4. The extent od the LiDAR coverage only enabled the slopes above the highway to be investigated with the other side of the valley not covered by the LiDAR survey. Studying the other side of the valley for slope hazards and identifying potential alternative alignments is part of the long-term management plan and would provide a more complete understanding of the hazards and options available to highway managers.

5. This study has demonstrated the effectiveness of using LiDAR to map the geomorphology and identify landslide features and slope hazards that are unable to be detected by observations of air photos and flyovers. The principles demonstrated in this study can and should be applied to other corridors in New Zealand where dense vegetation obscures the ground surface hiding slope hazards. It is no longer acceptable to say that we did not know, as tools now exist to identify the previously unidentifiable hazards and enable treatment to be implemented.

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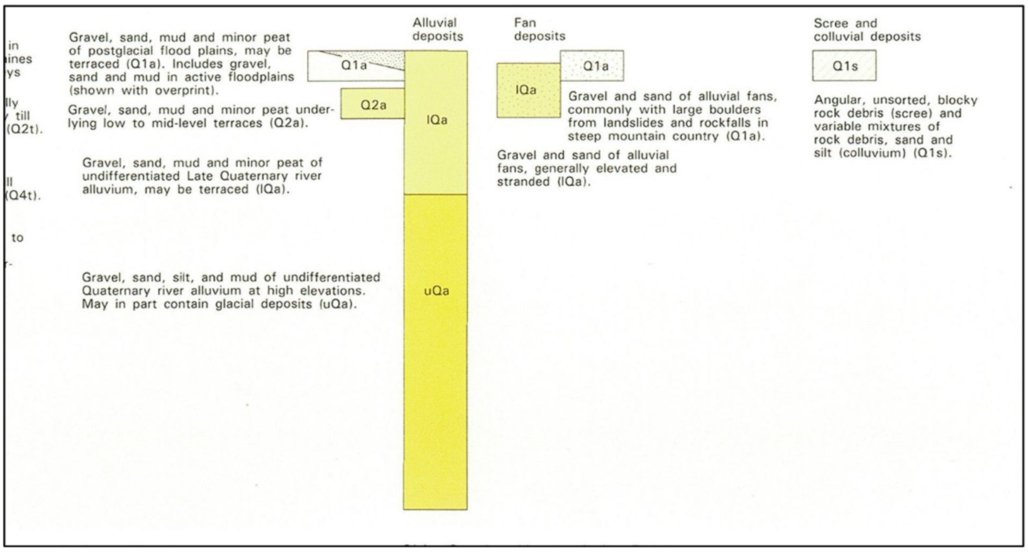
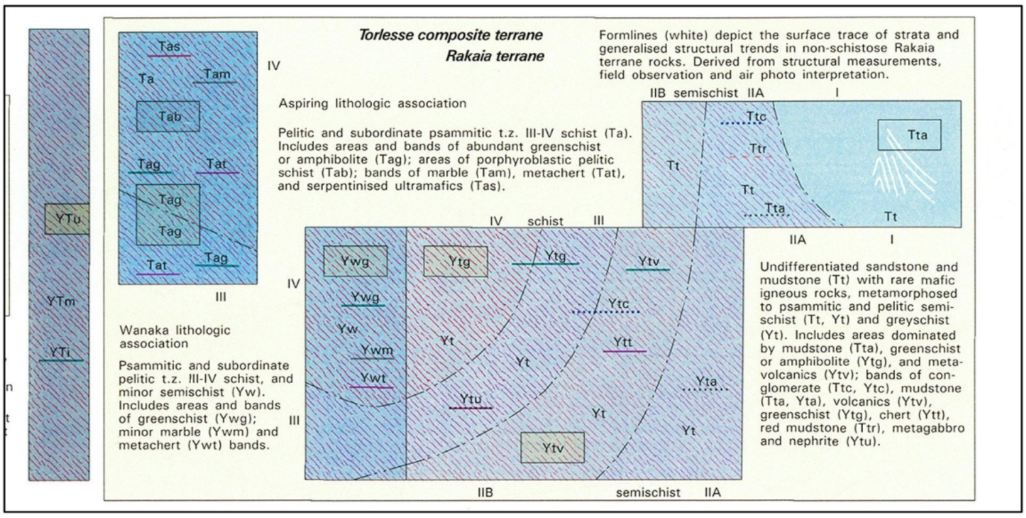
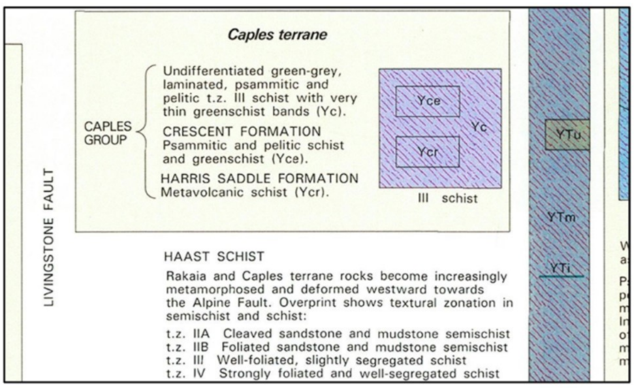
Appendix A
Relevant sections from the Haast Geological Map key for Figure 1.2 (Rattenbury et al. 2010)







Appendix B

Mass Movement Classification Table from Hungr et al. (2013)

Type of movement	Rock	Soil
Fall	1. *Rock/ice* fall[a]	2. *Boulder/debris/silt* fall[a]
Topple	3. Rock block topple[a]	5. *Gravel/sand/silt* topple[a]
	4. Rock flexural topple	
Slide	6. Rock rotational slide	11. *Clay/silt* rotational slide
	7. Rock planar slide[a]	12. *Clay/silt* planar slide
	8. Rock wedge slide[a]	13. *Gravel/sand/debris* slide[a]
	9. Rock compound slide	14. *Clay/silt* compound slide
	10. Rock irregular slide[a]	
Spread	15. Rock slope spread	16. *Sand/silt* liquefaction spread[a]
		17. Sensitive clay spread[a]
Flow	18. *Rock/ice* avalanche[a]	19. *Sand/silt/debris* dry flow
		20. *Sand/silt/debris* flowslide[a]
		21. Sensitive clay flowslide[a]
		22. Debris flow[a]
		23. Mud flow[a]
		24. Debris flood
		25. Debris avalanche[a]
		26. Earthflow
		27. Peat flow
Slope deformation	28. Mountain slope deformation	30. Soil slope deformation
	29. Rock slope deformation	31. Soil creep
		32. Solifluction

For formal definitions of the landslide types, see text of the paper.

[a] Movement types that usually reach extremely rapid velocities as defined by Cruden and Varnes (1996). The other landslide types are most often (but not always) extremely slow to very rapid

Appendix C

Cruden and Varnes (1996) Landslide Feature Classification

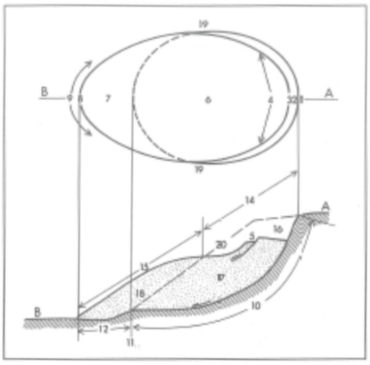


FIGURE 3-4
Landslide features: *upper portion*, plan of typical landslide in which dashed line indicates trace of rupture surface on original ground surface; *lower portion*, section in which hatching indicates undisturbed ground and stippling shows extent of displaced material. Numbers refer to features defined in Table 3-3 (IAEG Commission on Landslides 1990).

Table 3-3
Definitions of Landslide Features

NUMBER	NAME	DEFINITION
1	Crown	Practically undisplaced material adjacent to highest parts of main scarp
2	Main scarp	Steep surface on undisturbed ground at upper edge of landslide caused by movement of displaced material (*13*, stippled area) away from undisturbed ground; it is visible part of surface of rupture (*10*)
3	Top	Highest point of contact between displaced material (*13*) and main scarp (*2*)
4	Head	Upper parts of landslide along contact between displaced material and main scarp (*2*)
5	Minor scarp	Steep surface on displaced material of landslide produced by differential movements within displaced material
6	Main body	Part of displaced material of landslide that overlies surface of rupture between main scarp (*2*) and toe of surface of rupture (*11*)
7	Foot	Portion of landslide that has moved beyond toe of surface of rupture (*11*) and overlies original ground surface (*20*)
8	Tip	Point on toe (9) farthest from top (*3*) of landslide
9	Toe	Lower, usually curved margin of displaced material of a landslide, most distant from main scarp (*2*)
10	Surface of rupture	Surface that forms (or that has formed) lower boundary of displaced material (*13*) below original ground surface (*20*); mechanical idealization of surface of rupture is called *slip surface* in Chapter 13
11	Toe of surface of rupture	Intersection (usually buried) between lower part of surface of rupture (*10*) of a landslide and original ground surface (*20*)
12	Surface of separation	Part of original ground surface (*20*) now overlain by foot (*7*) of landslide
13	Displaced material	Material displaced from its original position on slope by movement in landslide; forms both depleted mass (*17*) and accumulation (*18*); it is stippled in Figure 3-4
14	Zone of depletion	Area of landslide within which displaced material (*13*) lies below original ground surface (*20*)
15	Zone of accumulation	Area of landslide within which displaced material lies above original ground surface (*20*)
16	Depletion	Volume bounded by main scarp (*2*), depleted mass (*17*), and original ground surface (*20*)
17	Depleted mass	Volume of displaced material that overlies surface of rupture (*10*) but underlies original ground surface (*20*)
18	Accumulation	Volume of displaced material (*13*) that lies above original ground surface (*20*)
19	Flank	Undisplaced material adjacent to sides of surface of rupture; compass directions are preferable in describing flanks, but if left and right are used, they refer to flanks as viewed from crown
20	Original ground surface	Surface of slope that existed before landslide took place

Appendix D
LiDAR Survey Coverage and Tiles

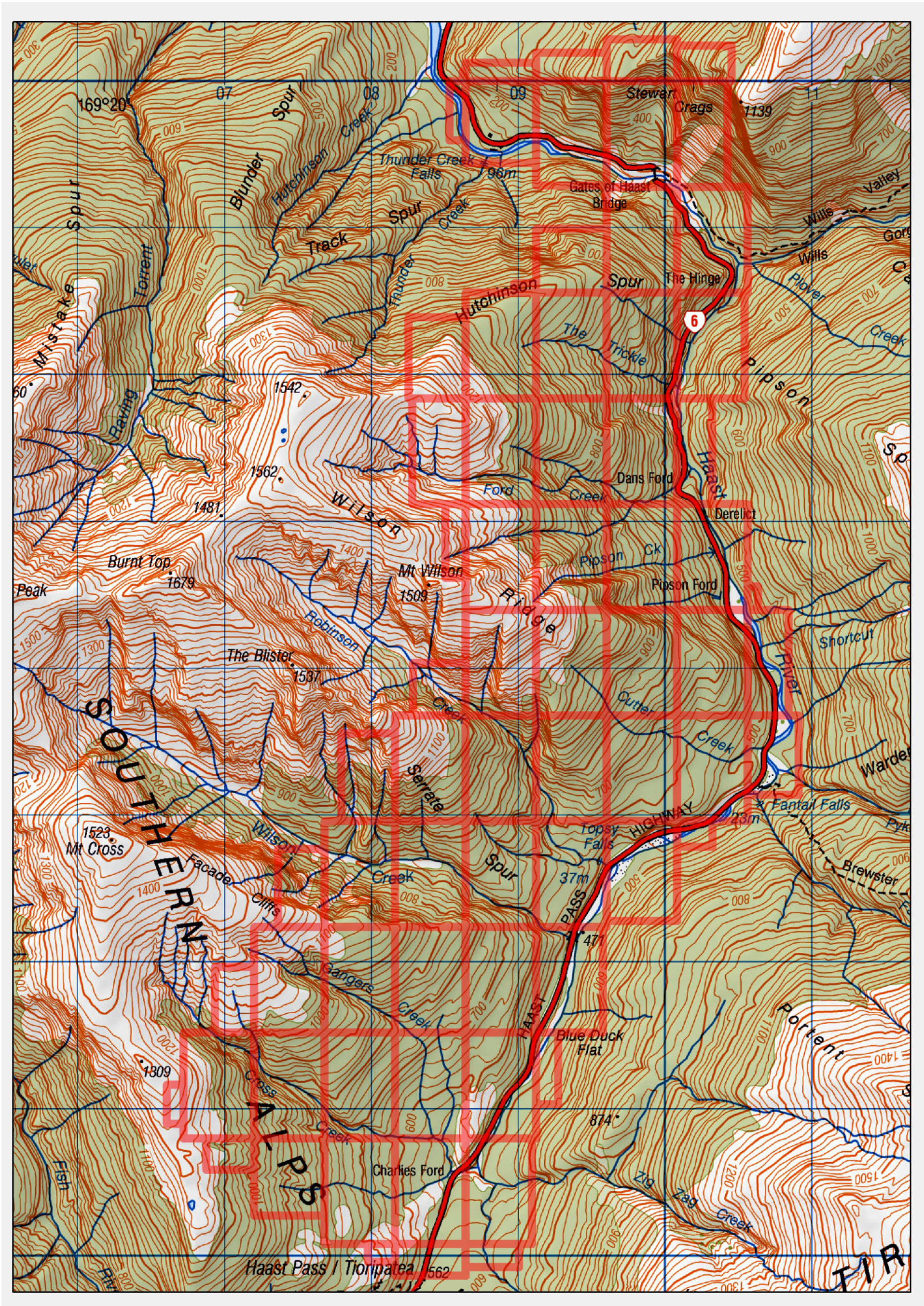


Figure 1: Extent of the LiDAR coverage and the break up of the LiDAR survey into the 72 tiles are shown by the red boxes over the topographic map of the field area. The topographic map is the New Zealand Topo 50 series map BZ13 - Haast Pass / Tioripatea.

Appendix E
Gates of Haast Historic Aerial Photo

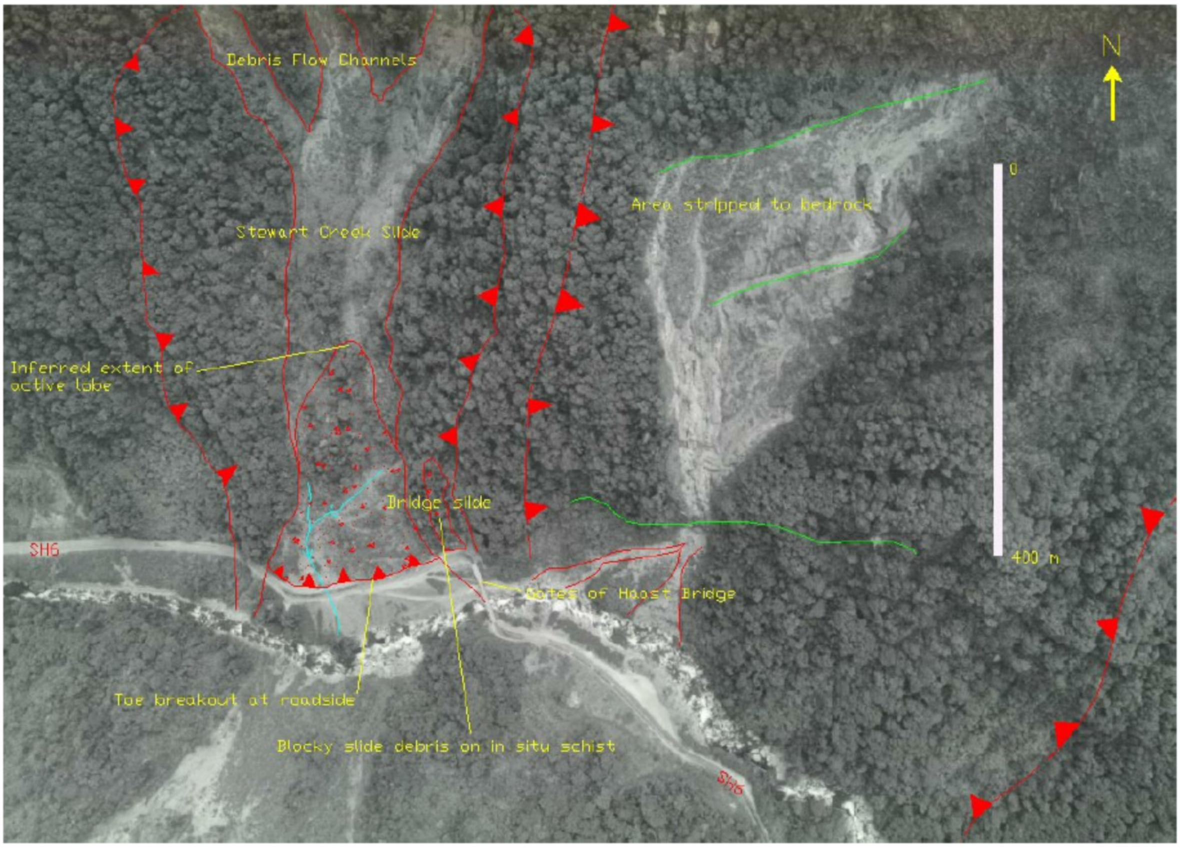


Figure 2: Annotated aerial photograph taken in 1992 showing the active debris flow/slide channels and the active nature of the slope processes (Opus 2001).